AFIT/GSO/ENS/93D-15

A Methodology to Assess the Impact of
the Global Positioning System on
Air Combat Outcomes

THESIS

Stephen F. Sovaiko
Captain, USAF

AFIT/GSO/ENS/93D-15

Best
Available
Copy

AFIT/GSO/ENS/93D-15

A Methodology to Assess the Impact of the Global Positioning System on Air Combat Outcomes

THESIS

Presented to the Faculty of the Graduate School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science (Space Operations)

Stephen F. Sovaiko, B.S., M.S.

Captain, USAF

December, 1993

Thesis Approval

Student: Captain Stephen F. Sovaiko, USAF

Class: GSO–93D

Thesis Title: A METHODOLOGY TO ASSESS THE IMPACT OF THE GLOBAL POSITIONING SYSTEM ON AIR COMBAT OUTCOMES

Defense Date: November 23, 1993

Committee:	*Name/Title/Department*	*Signature*
Advisor:	GREGORY S. PARNELL, Col, USAF Head Department of Operational Sciences Graduate School of Engineering	G S Parnell
Reader:	THOMAS S. KELSO, Lt Col, USAF Assistant Professor of Space Operations Department of Operational Sciences Graduate School of Engineering	Thomas Sean Kelso
Reader:	ROGER C. BURK, Maj, USAF Assistant Professor of Operations Research Department of Operational Sciences Graduate School of Engineering	Roger C Burk

Acknowledgements

This thesis is dedicated to the memory of a close friend, Captain Art Galvan, and the crewmen of Spirit 03, whose AC-130H Spectre gunship was lost during the battle for Khafji, 31 January 1991.

After having completed the toughest of my years in school, I think I finally realize how much we are buoyed by the people we are working with. I am forever grateful for the help and tutoring my friends in the GSO-93D class provided me. Craig Adams and Spike Schalck proved to be two of the most faithful friends a man can have. Lieutenant Colonel T.S. Kelso provided invaluable assistance by developing and providing GPS-related software for use in my modeling. I sincerely appreciate the nights and weekends he sacrificed for this effort. Captain John Anton at AFSPACECOM/DRF helped me through some very tough problems; his prior AFIT experience helped me narrow the scope of my research. Colonel Greg Parnell was a wonderful mentor and advisor who kept me on track, while letting me stub my intellectual foot once in a while to remind me that mistakes are still painful. As a Godly man, he also provided an inspiration for my personal, family, and spiritual life.

Most importantly, my wife Geri has supported me through every exam, briefing, and pressure of my Air Force career. Never failing, never critical, she has been the lovely anchor of my life, always reminding me of the strength of Christ that sustains me. Geri has suffered and rejoiced with me; I eagerly look forward to the return of our special times that were sacrificed while at AFIT. And to my sons Josh and Jason - I'm sorry for the countless nights and weekends that I wasn't there to enjoy life with you, but it is all behind us now, guys. Finally, I thank the Lord who has so generously blessed me with a wonderful family, friends, and career.

Stephen F. Sovaiko

Table of Contents

Page

Page

List of Figures

List of Tables

List of Abbreviations

Abbreviation Page

AFIT/GSO/ENS/93D-15

Abstract

The Air Force has a requirement to quantify the force enhancement effects of military space systems, but no methodology currently exists for the measurement of their contribution to air combat outcome. This research examines the Global Positioning System (GPS) and models its influence on air-to-ground combat. The decision analysis technique of influence diagrams is used to identify the effects of GPS launch decisions and constellation size on the navigation accuracy available to air combatants. The effect of accuracy variations on combat outcome is shown by using a value tree to identify the affected campaign Measures of Effectiveness. The study reveals that the use of GPS for navigation and weapons guidance results in a significant increase in sortie lethality that depends on the actual probabilities of survival, engagement, and kill for various weapon, platform, and target combinations. Also, the simultaneous loss of several GPS satellites is shown to have only a moderate time-averaged effect on navigation and combat outcome in the Northeast and Southwest Asia theaters. The methodology presented can be adapted to the study of other military space systems.

A Methodology to Assess the Impact of the Global Positioning System on Air Combat Outcomes

I. Introduction

1.1 Problem Statement

Most military decision makers perceive that the success of modern military operations depends on force enhancement from Department of Defense satellite constellations. General Charles Horner, commander of US Space Command, recently stated that "Space has become critical to modern war fighting" (13) and "will be vital to any future conventional conflict" (4). In spite of this emphasis on the value of space systems, there is currently no methodology available to quantify the military campaign value of a complete or partial military satellite constellation. The Air Force requires this decision aid to ensure that space systems programming and budgeting decisions provide the maximum effectiveness per dollar (18).

1.2 Background

Due to budget constraints and the growing dependence on space systems, the Air Force requires decision models and analyses to help make difficult procurement decisions. For satellite constellations, analysts use simulations to determine the schedule for replenishing a given constellation, to ensure its availability to intended users. Over the past two years, the Air Force Studies and Analysis Agency (AFSAA) developed a technique to evaluate satellite and launch vehicle procurement options during the programming and budgeting phases of the Air Force resource allocation process. The current Inventory Replacement Intervals for Satellites (IRIS) method-

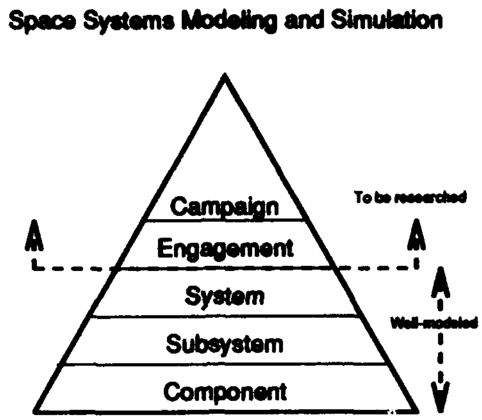

Figure 1. Hierarchy of Military Modeling and Simulation

ology uses launch vehicle and satellite reliability data, together with hardware procurement plans, to calculate the probability of achieving and maintaining the desired constellation over time (15). This measure of system availability has been very useful in comparing risk between different satellite procurement and launch interval options.

Figure 1 depicts the hierarchy of military modeling and simulation. The Air Force currently models the performance of space system components, subsystems, and systems, represented by the lower levels of the hierarchy. As shown in the upper portion of Figure 2, AFSAA uses the IRIS simulation to model the constellation size resulting from possible launch and spare inventory decisions, but this level of modeling does not support the analysis of space system effectiveness. Thus, they have no methodology that can compare the military value of one constellation configuration with another.

1.3 Research Scope and Objectives

The primary objective of this research is to provide a method to readily assess the potential effects of varying satellite constellation size on campaign outcome. The research advances the analysis of space systems' operational effectiveness from the current system-level models into the campaign-level tier. Due to the magnitude of

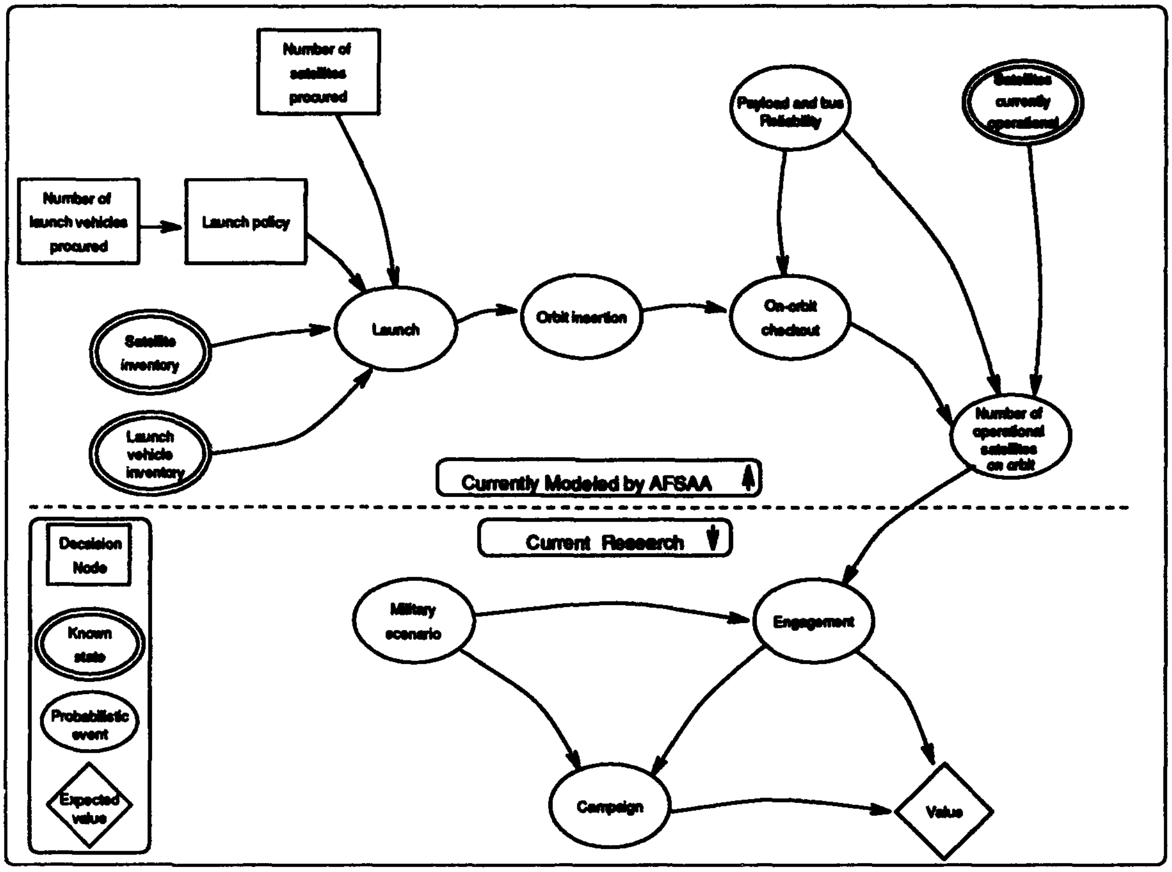

Figure 2. Influence Diagram Modeling Space System Contribution to Combat

the analysis problem, this research addresses only the Global Positioning System (GPS) constellation. The GPS campaign contribution model developed through this analysis will be used by the primary research sponsor, the Space and C^3I Division of AFSAA. As such, the model is designed for Air Force analysts and decision makers to use in comparing the consequences of GPS resource allocation decisions. These decisions affect the expected constellation size over time, and thus include some risk concerning the availability of GPS during a possible future campaign. This model will use decision analysis techniques to identify and concentrate on the most significant contributions of GPS navigation to combat outcome. The potential use of this method for other, non-GPS, military space systems will also support the interests of SMC/XR, which has a need to define the operational contribution of Air Force space systems (12).

A secondary objective is the investigation of potential enemy use of GPS against our own forces. The worldwide proliferation of inexpensive GPS navigation systems poses a new threat to our current navigation advantage, and the issue has received recent Air Force Chief of Staff attention (10). To accommodate these concerns, the research will develop a means to characterize the impact of enemy exploitation of the GPS signal. This method will provide the National Air Intelligence Center (NAIC) with an analysis tool to further investigate these issues.

1.4 Use of Decision Analysis

Decision analysis is the study of modeling complex, multi-objective decisions that include uncertainty and preferences (6). By applying decision analysis techniques to the GPS campaign contribution problem, we will:

- Use influence diagrams to identify the model structure of the space system combat contribution problem.
- Use a value tree to readily identify the multi-tiered, interdependent effects of space systems in combat.

- Use simulation to provide a means to forecast combat results as a function of varying space systems' resources.

1.5 *Overview of Thesis*

Chapter II presents the essential characteristics of the GPS constellation and its application to navigation. A brief review of previous research in modeling the GPS campaign contribution provides a foundation for the methodology in this thesis. This chapter also summarizes the major system-level assumptions used in developing the thesis.

Chapter III describes the development of a GPS campaign contribution methodology. Each model variable or parameter and its associated assumptions are identified.

Chapter IV is a review of analytical results obtained with the model. Sensitivity analyses are presented and the model behavior is discussed.

Finally, Chapter V summarizes the research, presents significant findings, and draws conclusions. Suggestions for follow-on study are presented as an aid to future research.

II. Modeling the Contribution of GPS

The modeling of the GPS system's contribution to campaign outcomes requires a basic understanding of the characteristics of the system and knowledge of previous attempts to model the GPS campaign contribution. This chapter outlines the aspects of the GPS system that are critical to simulation, and the approaches used in previous analyses. The reader is referred to the GPS NAVSTAR User's Overview (11) for a more detailed description of the GPS system.

2.1 GPS Navigation System

The military services are interested in the use of satellite radio frequency transmissions for time, space, position, and navigation information. For almost 30 years, increasingly sophisticated space systems have proven the feasibility of satellite-based navigation. The efforts of the GPS Joint Program Office (JPO) have resulted in the deployment of a highly accurate space-based positioning, velocity, and time system for worldwide use.

The GPS system transmits signals of two code types. The Standard Positioning Service (SPS) signal is provided for civilian use, and is sometimes referred to as coarse acquisition (C/A) code. The higher accuracy Precise Positioning System (PPS) code, or P-code, is available only to authorized military or DoD users who have access to the classified code parameters. The SPS and PPS accuracy specifications are listed in Table 1.

The GPS system consists of three major components: the space, control (or ground), and user segments. Each is briefly described below.

2.1.1 Space Segment. The GPS space segment, currently approaching full operational capability, will consist of 24 active satellites distributed among six orbital planes (8). Each plane contains four satellites spaced asymmetrically to optimize

Table 1. GPS Accuracy Specifications
(11:59)

	SPS	PPS	Measurement Type
Position Accuracy	76 m	16 m	Spherical Error Probable
	40 m	8 m	Circular Error Probable
Velocity Accuracy	N/A	0.07 m/sec	Linear Error Probable
Time Accuracy	115 nsec	68 nsec	Time Error Probable

ground coverage in the event of a failure. The 24 satellites (known in the GPS community as Space Vehicles, or SVs) operate in near-circular orbits at an average 20,200 km altitude and 55 degree inclination. The selected altitude and eccentricity result in a semi-synchronous orbit with a period of one-half sidereal day (11 hours, 58 minutes, 2 seconds). This causes the same set of SVs to appear over a fixed user location for the same duration each day, but rising and setting four minutes earlier on each successive day.

The spacing of SVs in the six planes will provide at least five SVs in view above the horizon at any location worldwide. SVs below five degrees elevation are generally considered unusable due to the significant path delay and atmospheric attenuation. Only four of the five visible SVs are required for an accurate position fix; three satellites are used to determine three-dimensional position and the fourth provides time information.

The SVs transmit on two L-band frequencies, L1 and L2. L1 (1575.42 MHz) broadcasts a P-code and C/A-code signal, while L2 (1227.6 MHz) transmits P-code only. Only one of these frequencies is necessary for P-code reception, but dual-frequency use yields high accuracy results by detecting and compensating for ionospheric delay errors.

The initial RDT&E constellation consisted of Block I SVs built by Rockwell; ten reached orbit between 1978 and 1985 aboard the Atlas-Centaur and three are

still operational and may triple their five-year design life (11:44). Experience from Block I testing led to improved SV subsystem design in the 30-SV Block II buy, of which 22 SVs have been delivered and are currently on orbit. Future plans include the delivery of 20 additional Block IIR SVs, slated for launch beginning in 1995.

2.1.2 Control (Ground) Segment. The GPS Control Segment is composed of a master control station, various S-band command antennas, and signal monitoring stations. Maintenance of the GPS constellation requires at least one master control station, one command antenna, and one signal monitoring station (11:62).

The master control station (MCS), which provides computational support for the entire control system, is operated by AFSPACECOM's 2nd Satellite Control Squadron located at Falcon AFB, CO. Currently, only the MCS can maintain the GPS system navigation accuracy; the MCS computes daily housekeeping and stationkeeping commands for the SVs. The MCS also prepares an updated navigation message for each SV, including a detailed almanac containing the ephemeris and health (operational) status for each on-orbit SV. This navigation message is imbedded (via Modulo-2 addition) in the P- or C/A-code SV signal for use by any GPS receiver. Plans for the construction of a redundant MCS and the autonomous ability of Block IIR SVs to maintain their orbital systems and navigation messages via satellite crosslinks will reduce dependence on the MCS.

Three unmanned command antennas, under the control of the MCS, are located at Kwajalein Atoll, Ascension Island, and Diego Garcia. These facilities provide MCS access to the entire GPS constellation via an S-band uplink. Only one antenna is required to maintain the entire GPS system. If necessary, a non-dedicated antenna is available at Cape Canaveral AFS, FL.

In addition to the MCS and ground antennas there are five monitoring stations, located at Oahu, HI; Falcon AFB, CO; Kwajalein Atoll; Ascension Island; and Diego Garcia. These locations monitor the raw 50 Hz SV navigation messages and status of

onboard systems (or SV health). Currently, the navigation messages are continuously monitored and relayed to the MCS where new uploads are prepared for ground antenna transmission to the satellites every 24 hours. The health status for each satellite is determined by the MCS and uploaded via ground antennas two to three times daily, for subsequent inclusion in the GPS navigation messages.

If the required combination of master control system, command uplink antenna, and monitoring station were not available, the first effect on the GPS space system would be degraded onboard accuracy within 48 hours. Civilian user equipment is designed to rely on the satellite's self-reported time and ephemeris data to complete a position fix, and would be unable to correct for the errors. Military user equipment should not lose accuracy for about 14 days, as the user hardware includes better clocks and the ability to detect and correct satellite errors. This system performance characteristic is known as 'graceful degradation.' The more autonomous Block IIR satellites will be able to maintain onboard full accuracy for at least 180 days after loss of the MCS, retaining full accuracy for both civilian and military users (19).

The second effect from continued lack of uploads to the satellites is the degradation of satellite health and, ultimately, the loss of satellite availability. These effects occur long after accuracy has begun to degrade, and impact all users.

2.1.3 User Segment. The user segment of the GPS system is the user equipment that provides navigation information derived from the GPS SV signals. This segment contains a widely assorted array of equipment for military and civilian purposes, but all user architectures have some fundamental components in common. All must have an L-band reception antenna, a phase-modulation receiver (to track the GPS C/A- or P-code signals), and a data processor to calculate position and time information from a minimum of four available SVs.

2.2 *Measures of Performance for the GPS System*

The GPS system performance is usually quantified by a measure of the navigation accuracy obtained from the user's GPS receiver. The navigation accuracy is predicted at a specific time by using a dilution of precision (DOP) algorithm, and the time- and location-averaged satellite availability is the basis for a constellation value measure.

2.2.1 Dilution of Precision. As the system is degraded, the resultant GPS accuracy is also reduced. Navigation accuracy is a function of two variables: the user range error to a single satellite, and the dilution of precision resulting from satellite geometry relative to the receiver. User equivalent range error (UERE), measured in meters, is associated with the satellite signal stability and quality of the receiving equipment, but it can be assumed constant for a specific receiver. DOP is a unitless parameter used to quantify and compare the user's location uncertainty as a consequence of SV location relative to the user's position; DOP varies over time as the SVs and user move. The DOP can be easily predicted and the set of four SVs with the lowest DOP are selected for each navigation computation. One-sigma GPS accuracy is equal to the UERE times the position (or three-dimensional) DOP (PDOP) for a specific location and time.

Although DOP can be predicted throughout its variations, the effect of DOP on weapons or navigation accuracy can be minimized by conducting critical missions during periods of the lowest daily DOP and the resulting higher accuracy. The higher average DOP values that accompany a severely reduced constellation will, however, result in degraded GPS navigation performance. This effect will be more thoroughly discussed in Chapter III.

2.2.2 Constellation Value. DOP varies with the number of available SVs and the time and location of observation. Because these variables are uncertain for possible military campaigns, it is difficult to predict future GPS accuracy results.

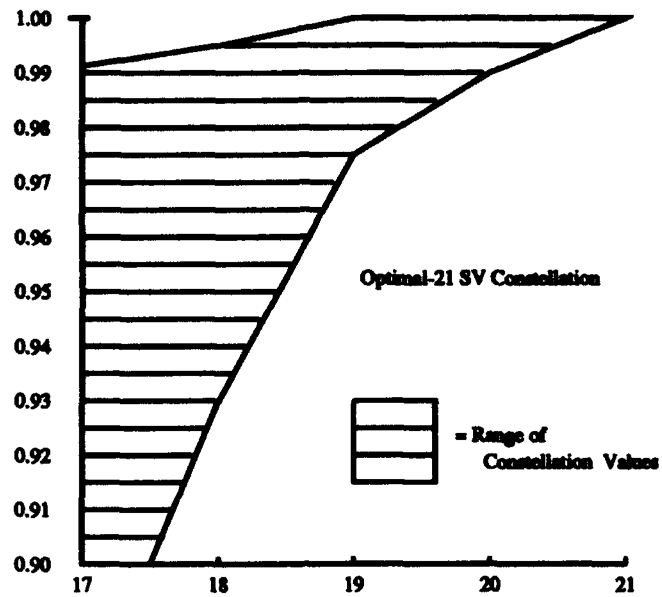

Figure 3. PPS Constellation Value vs Number of SVs (11:67)

However, a useful forecast of system performance can be obtained from constellation value.

The constellation value is the fraction of all possible times and locations within the geographic region of interest that have four SVs with a DOP that provides accurate navigation information (11:66). The constellation value can be computed for the SPS, PPS, 2-dimensional, and 3-dimensional cases. The GPS user community's arbitrary definition of 'sufficient DOP' is a 3-dimensional PDOP less than or equal to 6.0, and a 2-dimensional horizontal DOP (HDOP) less than or equal to 4.0. Although these values do not correspond to the GPS accuracy specification thresholds as seen in Table 2, they have become widely accepted as a minimum threshold for accurate GPS navigation (11:64).

A constellation value of less than 1.000 indicates that some global locations experience periods of poor DOP or fewer than four SVs in view. As shown in Figure 3, the Optimal-21 constellation (a predecessor to the current 24 SV configuration)

Table 2. Comparison of DOP Thresholds to PPS GPS Accuracy

DOP	PPS UERE	Derived Accuracy	PPS Specification
6.0 PDOP	7m	38m SEP	16m SEP
4.0 HDOP	7m	23m CEP	8m CEP

yielded a PPS 3-dimensional constellation value of 0.9999. Any SV losses that reduce the number of functional SVs below the baseline 21 cause the lower bound of possible constellation values to also drop. The 24 SV constellation behaves similarly.

Together, the DOP forecast and constellation value provide a straightforward means to quantify the availability of the GPS SVs and the system accuracy for large scenarios.

2.2.3 Constellation Size. The size of the GPS constellation is a function of successful constellation build-up launches, satellite failures, and successful replacement of the failed SVs. The constellation size at any time can be forecast using one of several models. Although AFSPACECOM uses the Operational Satellite Constellation Availability and Reliability Simulation (OSCARS) and the GPS JPO uses the General Availability Program (GAP), AFSAA uses the IRIS model developed by ANSER Corporation for SAF/AQ. Because AFSAA utilizes IRIS exclusively, the IRIS model was selected for this research.

IRIS is a Monte Carlo simulation of SV failures over time (15). Given a current on-orbit inventory, launch inventory, and replacement schedule, IRIS uses a Rayleigh-truncated Weibull or combined Weibull and Normal distribution to predict satellite failures (Table 3). The mean mission duration, Weibull shape and scale parameters, and maximum lifetimes are based on observed data. IRIS also accommodates spacecraft reliability[1], launch vehicle reliability, and launch pad constraints

[1]Spacecraft reliability is the probability the satellite will initialize and properly function upon reaching orbit.

Table 3. Satellite Reliability Parameters

Parameter	BLOCK IIA	BLOCK IIR
Weibull Alpha	138.6	193.0
Weibull Beta	1.60	1.34
Max Life (months)	120	200
Normal Mean	90	120
Normal Std Dev	12	12

in determining the minimum time between routine launches and minimum time to recover from failed launch attempts. For this simulation, the IRIS input parameters in Table 4 were obtained from an AFSPACECOM/DRF baseline for GPS simulation (14). The use of this baseline ensured that the simulation was comparable to existing GPS constellation size forecasts. The IRIS simulation consisted of 100 independent runs.

Two satellite configurations were modeled in IRIS, the Block IIA and the Block IIR SVs. Thus, any Block I SVs still in operational status are not contributing to the IRIS constellation forecast.

2.3 Identifying the Campaign Contribution of Space Systems

Before any military system can be modeled, measures of effectiveness and outcome must be identified. For the modeling of space systems, previous analysis provided results useful to this research.

2.3.1 Measure of Outcome Selection. The identification of an appropriate measure of outcome (MOO) for the contribution of space systems to campaigns has received significant attention in recent years. Lt Gen Glenn A. Kent (USAF, Ret) of the RAND Corporation proposed the use of time to achieve campaign objectives as the most useful measure of combat outcome (16). For the air-to-ground campaign scenario, the selected MOO for this research is the number of targets killed or

Table 4. Baseline IRIS Input Parameters

RUN PARAMETERS	
Space System Name	GPS
Number of Trials	100
Spacecraft Reliability	0.99
Launch Vehicle Reliability	0.95
Number of Launch Pads	1
Pad Turn-Around Delay (months)	2
Launch Delay on Spacecraft Failure (months)	3
Launch Delay on Vehicle Failure (months)	3
Spacecraft Call-up Delay Time (months)	3
Initial Date	SEP 1993
Number of Spacecraft in Constellation	24
Number of Spacecraft to be Launched	26
Number of Configurations	2
Spacecraft Availability Constraints	Y
Random Number Seed	15234

destroyed over 30 days. A key assumption was that if sufficient targets were killed quickly, the campaign could accelerate and minimize exposure to enemy threats and subsequent force losses.[2]

2.3.2 Measures of Effectiveness Selection. After identifying the time to achieve campaign objectives as the MOO best representing the real contribution of space in air combat, the next step is to identify specific engagement measures of effectiveness (MOEs) that represent the influence of space systems.

[2]A noteworthy example used by Gen Kent was the extensive use of *time* estimates in planning the Desert Storm campaign. According to Gen Kent, a primary concern of Gen Schwartskopf's was the time required to achieve campaign objectives. He was not as interested in the quantities of sorties, aircraft or munitions required to support the campaign; he pinned then-Lt Gen Charles Horner, Air Component Commander, and then-Brig Gen Buster Glossen, Director of Campaign Plans and Commander of the 14th Air Division (Provisional), to provide best estimates of the time it would take to achieve specific campaign objectives in the air war. At issue was the planned start of the ground war, which, to minimise allied losses, was contingent upon achieving an extraordinary imbalance of forces and destroying the enemy's will to fight through the use of air power.

A study by AFSPACECOM/CNP in 1992 identified a potential approach to evaluating these MOEs (22). Strategy-to-task ideas proposed by RAND (24) and in use at Air Combat Command were discussed by AFSPACECOM as a means to define the actual tasks that should be measured in the analysis of space systems' combat contributions. The authors suggested a flow-down of specific strategies through Air Force mission areas and tasks, but they did not complete the MOE identification in their research.

The MOE identification can, however, be facilitated by the decision analysis value tree technique. A value tree is a useful tool in situations where a decision influences multiple objectives (6:433). The construction of the tree helps the analyst identify the most basic objectives that are affected by the decision and the objectives' respective attributes (MOEs) that can be measured, weighted, and scored.

Previous research by RAND (2) described the primary air combat objectives enhanced by the use of GPS systems in a theater-level campaign. Each of these fundamental objectives could be reduced to more specific, detailed objectives to help identify their respective operational attributes. The use of the value tree technique highlighted the attributes that could be used as 'hooks' in a campaign model to determine the influence of GPS on combat outcome. This breakout is readily observed in the value tree shown in Figure 4.

The fundamental objectives enhanced by GPS navigation are the improvement of self location accuracy, target location accuracy, and the increased use of standoff launch tactics and munitions. These improvements are more specifically described by evaluating more detailed objectives and measuring their specific attributes.

Improved self location accuracy with GPS results in improved navigation ability and a possibly reduced incidence of fratricide. The most significant contributors for the air-to-ground interdiction mission are the improved ability to navigate, measured by an increased probability of correctly self-locating, increasing survivability,

Fundamental Objectives	Detailed Objectives	Attributes
Improved Self-Location Accuracy	Improved Navigation	- Increased sortie effectiveness and survivability - Higher average sortie rates - Increased P(kill) for iron bombs and inertially-guided weapons
	Reduced Fratricide	- Reduced force losses
Improved Target Location Accuracy	Additional Platforms Available to Provide Accurate Target Designation	More accurate fixes from: - E-8 Joint STARS - Special Forces (SOF) - RPVs
	Faster Production of Target Location Data	- Faster response time - Higher P(engagement) of time-sensitive targets
	Increased Lethality	- Higher P(kill) and P(engagement) due to more accurate target coordinates - Higher P(engagement) due to independence from weather and visibility - Fewer weapons required to destroy target set
Improved Use of Standoff Launch and Munitions	Reduced Vulnerability to Enemy Threats	- Increased proportion of smart weapons' use - Increased platform survivability - Higher average sortie rates

Figure 4. Value Tree for GPS Assets Used in Air-to-Ground Campaign

and, ultimately, sortie rates. For GPS-aided weapons, the probability of kill is also increased over inertially-guided systems.

The improved target location accuracy afforded by GPS increases the number of platforms available to provide accurate target location data by eliminating the observer's self location uncertainty. With more sensors providing more accurate target data, critical targets have a higher probability of being engaged. The faster production of target location data is realized by the elimination of conflicting coordinate systems and attendant uncertainty, increasing the likelihood of engaging time-sensitive targets. In addition, the increased certainty of target locations results in increased sortie lethality by requiring fewer weapons and threat exposures per target, since multiple-ship flights are the traditional hedge against target location uncertainty.

The use of GPS navigation also improves the ability to use standoff weapons and tactics. The most significant benefit of standoff use is the reduced vulnerability to enemy threats, which increases the platform survivability and subsequent sortie rates. The availability of less expensive 'smart' GPS munitions also results in higher proportions of smart munitions in the overall air-to-ground weapons mix. A secondary benefit of standoff use is the decreased range to engage targets and the shorter sortie turn times, but in relatively small theaters, these increases are minimal.

2.4 Attempts at Modeling the Campaign Contribution of GPS

The Analytical Sciences Corporation (TASC) and the RAND Corporation have developed methodologies to analyze the specific contributions of the GPS system. Two of their models are discussed in this section.

2.4.1 TASCFORM-SPACE. In 1991 TASC published a summary of their first attempt to model the campaign contribution of GPS (23). The TASCFORM-SPACE model identified three major factors influencing the contribution of GPS: the accuracy, the availability, and the survivability of the GPS system as shown in Figure 5. The survivability of the system was decomposed into three areas: signal, constellation, and ground segment survivability.

TASC used these three factors in a multiplicative function to produce a static MOE for a given campaign scenario, assuming the independence of each factor. The three factors were weighted and a unitless MOE obtained for any combination of contributing values. This treatment did not represent the actual behavior and interaction of the three contributors, which was outlined earlier in this chapter. This model is currently being reworked by TASC, but results were unavailable for review.

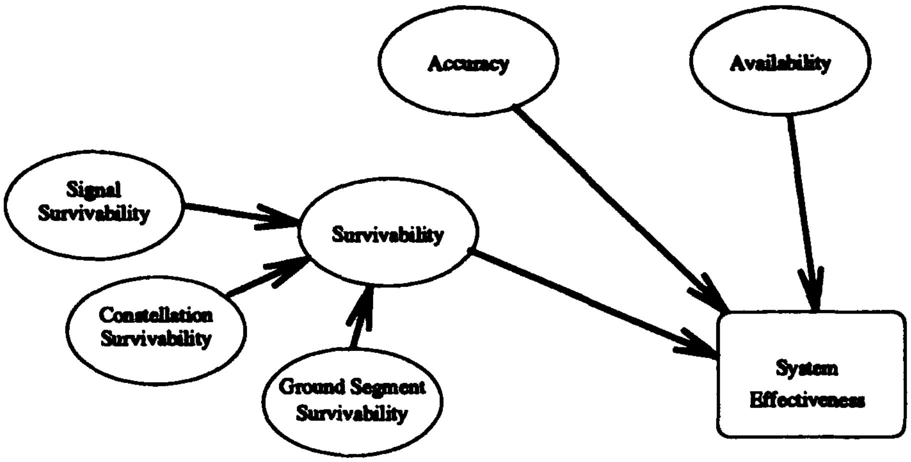

Figure 5. Influence Diagram Representing TASC's Algorithm.

2.4.2 RAND's Theater Level Conflict (TLC) Model. Current research by the RAND corporation for their Theater Level Conflict (TLC) model includes thorough treatment of GPS influences on air campaign tasks and their respective MOEs (2). While there are many large scale theater warfare simulations available to the analyst, TLC will be one of the first to model the effects of GPS. RAND's work in identifying the fundamental and secondary benefits of GPS navigation is very insightful, and was used in this thesis' model development as described in Section 2.3.2. The completed TLC model is projected to be available sometime in 1994.

With both TASCFORM-SPACE and TLC unavailable for this research, the requirement for the formulation of a GPS campaign contribution methodology remained.

2.5 GPS System Assumptions

As a result of this discussion of the GPS system, several important assumptions can be made. They will aid in the formulation of the GPS model in Chapter III.

1. For the assessment of ground segment survivability, the limited threat to the CONUS-based MCS is assumed not to impact military user accuracy during a short (30 day) campaign. While the civilian (C/A-code) user would experience a degradation in 24–48 hours, the P-code military user can obtain accurate navigation for at least two weeks. The modeled scenario is expected to occur in 1995 or later, when the autonomous Block IIR SVs begin populating the constellation and the MCS is less critical to short-term system performance.

2. The GPS space segment has limited nuclear and directed-energy hardening, a large numerical constellation size, and wide spatial separation. These attributes provide a hedge against the effects of limited anti-satellite (ASAT) attacks. Thus, the GPS constellation can be assumed to survive short-duration Southwest and Northeast Asia (SWA and NEA) scenarios (18).

3. GPS system availability is accurately modeled by the constellation value metric. GPS availability can be predicted to the second, but the high resolution is not required for a high-level campaign model. Constellation value, by time-averaging DOP over a geographic region, provides ample fidelity for this simulation.

4. Short-term degraded DOP can be avoided, and its impact on GPS accuracy will be negligible through a short campaign. While SV attrition causes significant DOP increases for short intervals, the increases are predictable, localized, and potentially avoidable by careful mission planning.

III. GPS Tactical Air Combat Simulation Model (TACSIM)

This chapter presents a method to model GPS availability and its contribution to the warfighter. The GPS Tactical Air Combat Simulation (TACSIM) model was developed to assess GPS system performance and campaign outcome; it is a combination of two smaller models simulating:

- GPS accuracy available to combatants.
- Air-to-ground combat conducted with and without GPS.

3.1 GPS Accuracy Available to Combatants

The major effort of this research was the modeling of the interaction between the GPS system and the campaign. An influence diagram (Figure 6) was used to identify the major variables driving the GPS system performance and the resultant accuracy available to the GPS user.

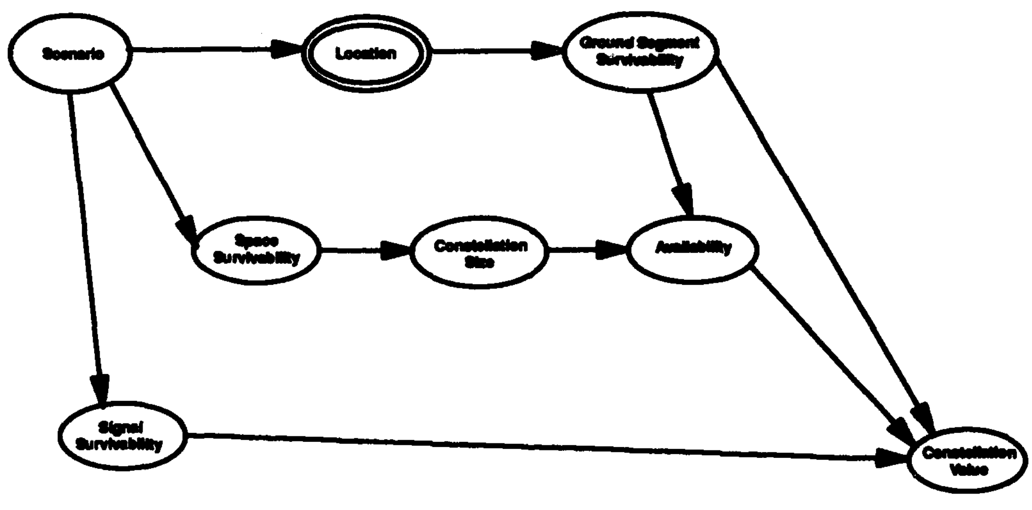

Figure 6. Influence Diagram Representing GPS System Performance

3.1.1 Scenario. The first node represents the scenario event; the scenarios were limited to SWA and NEA. These two scenarios were of highest interest to AFSAA analysts (18).

3.1.2 Location. Previous GPS availability studies by Aderhold (1) and Thomin (25) revealed some dependence of GPS system availability on location, especially as the constellation is reduced by attrition. Accordingly, the theater determines the geographic boundaries of the campaign, as outlined in Table 5. For ease of computation, the boundaries were defined as a rectangular area large enough to cover the respective theater.

Table 5. Location Boundaries for Theater Scenarios

THEATER	Maximum Latitude	Minimum Latitude	Minimum Longitude	Maximum Longitude
SWA	40N	30N	40E	50E
NEA	40N	35N	120E	130E

3.1.3 Signal Survivability. This node represents the event that the GPS signal survives the electromagnetic environment and is received by the intended user. But in some scenarios, the signal could be jammed or spoofed by enemy emitters. The spread-spectrum GPS PPS signal is below ambient RF noise level at about -163 dBW, but can be tracked as long as hostile jammer signals are less than 41 dB above the GPS signal level (11:40,74).

The actual enemy jamming threat is uncertain, but future scenarios may include some enemy effort to deny our use of GPS signals in high-value regions or target locations. The threat is further complicated because the magnitude of the GPS navigation error induced by the hostile jammer is unknown; it is a function of jammer power and platform INS drift rate. These variables are difficult to forecast.

The PPS GPS signals can also be spoofed, but the effect is limited, since authorised users can track an alternate, encrypted Y-code that is not spoofable (11). For this analysis, however, the jamming and spoofing threat is not characterised and the node merely represents the fact that GPS signal survivability is not certain; GPS signal survivability is assumed to approach 1.0 for both SWA and NEA scenarios.

3.1.4 Space Vehicle Survivability. As explained in Section 2.5, the GPS space survivability can be assumed to approach 1.0 for the SWA and NEA scenarios.

3.1.5 Ground Segment Survivability. The ground segment is assumed to survive the minimal threats posed during SWA and NEA campaigns, as discussed in Section 2.5.

3.1.6 Constellation Size. The constellation size forecast is the node which most significantly impacts GPS availability to the warfighter. The resource allocation decisions affecting constellation size are introduced through this node using the IRIS model output data. The outcome of this node is a probability distribution of the number of satellites in orbit, as shown in Figure 7. Full operational capability of the GPS constellation is scheduled for early 1994; thus the probability distribution is obtained from IRIS for 96 months beginning in March of 1994. This baseline distribution is for the current inventory of Block II SVs and the published schedules for remaining launches (14).

3.1.7 Satellite Availability. The satellite availability is a function of user location, time of observation, and the orbital locations of the operating SVs.

- User location is defined by the scenario of interest.
- The time of observation is uncertain, due to unknown start and duration times of the campaign. This problem is overcome by using current GPS ephemeris

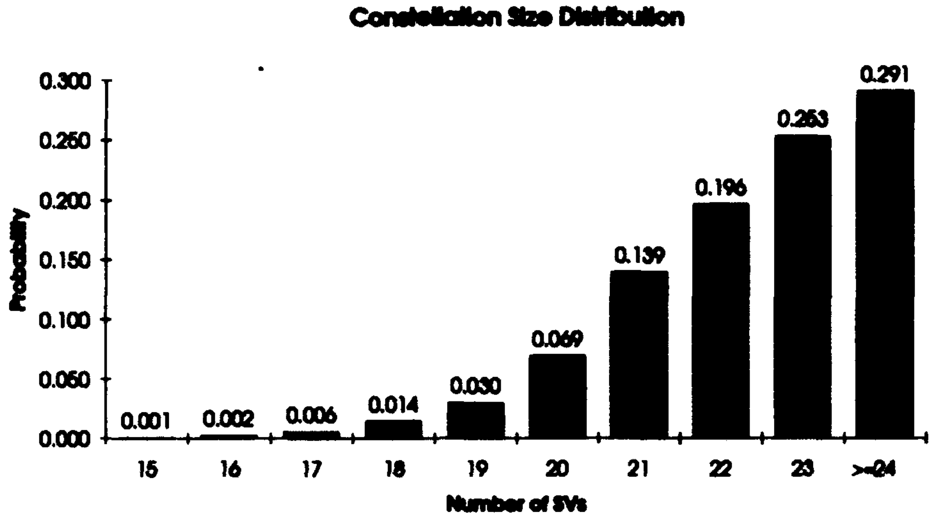

Figure 7. Discrete Probability Distribution for GPS Constellation Size, 96 months beginning in March 1994

data to compute PDOP and constellation value, and assuming that it represents any future constellation within the eight year planning horizon.

- The orbital locations of the operating GPS SVs must be characterized, as certain combinations of failures can impact some locations and times more severely than others.

3.1.7.1 Suboptimal (< 24 SV) Constellation Configurations. For accurate DOP predictions, the future constellation configuration must be accurately forecast. Unfortunately, the IRIS simulations do not identify specific SV failures, but merely generate the expected number of operational SVs at a future date.

In the most thorough analysis, the accuracy of DOP predictions relies on the accuracy of the ephemeris data and SV status for the time frame of interest. As SVs fail, they should be removed from the operational SV list, and the fourth SV in each plane will likely be maneuvered to minimize the impact of the failure to DoD users. In some cases, the failed SVs will have negligible impact to the observer's DOP. In more severe cases, such as multiple failures in adjacent planes, the DOP

Table 6. SV Availability Degradation Due to SV Attrition (18 SV Constellation)

SV Failures	Best CV	Worst CV
0	0.9945	0.9945
1	0.9770	0.9768
2	0.9522	0.9200
3	0.9220	0.8416

will be significantly degraded. Thomin's data, as shown in Table 6, demonstrate that for a random selection of failures in the one-, two-, and three-failed-SV cases, the PDOP-dependent constellation value (CV) varies significantly (25:34). The range of values for each failure scenario may be wider than the data indicate if all the possible failure combinations are considered.

While the data in Table 6 and Figure 3 were generated for a preliminary (18 SV) constellation, it does demonstrate DOP sensitivity to specific combinations of SV failures. The computation of DOP values for each failure combination requires manipulation of the GPS constellation almanac, or satellite ephemeris file, to delete the failed SVs. For one SV failure, this is a manageable effort. But for two or more SV failures, the problem becomes difficult due to the number of combinations involved.

This exhaustive analysis was not performed for the TACSIM model; instead, the PDOP values were computed for 30 random combinations of SV failures in each likely failure scenario. Based on the data in Figure 7, there is only a 1% cumulative probability of experiencing 7 or more simultaneous SV failures; therefore, the analysis was only performed for cases of six or fewer failures.

To accomplish this analysis, a PDOP calculation program was developed by Lieutenant Colonel T.S. Kelso at AFIT/ENS. The PDOP computations for each failure combination were performed in one-minute time steps over 24 hours[1] in both

[1]PDOP computations were performed for the period 0000 UTC 1 Nov to 0000 UTC 2 Nov 1993.

Table 7. Constellation Value (CV) Results for 30 Random Samples

	SWA			NEA		
SVs Deleted	Min	Mean	Est Error from Mean	Min	Mean	Est Error from Mean
0	1.000	1.000	N/A	1.000	1.000	N/A
1	0.976	0.999	N/A	0.958	0.997	N/A
2	0.976	0.999	0.001	0.955	0.990	0.004
3	0.911	0.984	0.007	0.885	0.975	0.010
4	0.869	0.975	0.008	0.887	0.967	0.008
5	0.845	0.945	0.013	0.829	0.936	0.014
6	0.798	0.918	0.015	0.795	0.897	0.017

the SWA and NEA theaters at one-degree intervals of longitude and latitude. The current inventory of 23 Block II SVs was used along with one Block I (SVN 11) to represent a full constellation.

3.1.8 GPS Accuracy. Variations in GPS system accuracy can be approximated by comparing CV values; when SV attrition causes CV values to decrease, a higher proportion of GPS users will experience degraded navigation accuracy. This characteristic is used to tie the GPS system model to the air combat model.

For each of the 348 PDOP runs[2], the fraction of 24 hours that experienced PDOP ≤ 6.0 was calculated at each location step (one-degree of latitude/longitude), and the mean CV for the theater area computed. As seen in Table 7, the sample means remain above 0.89 even when 6 SVs are removed, and the maximum CV value for all cases is 1.00. The estimated errors from the true population means range from 0.001 to 0.017, suggesting that the sample size of 30 is adequate to model the mean CV for each scenario. A detailed description of the CV computation process is included in Appendix A.

[2]For the SWA theater, 24 runs were conducted for the 1 SV failure case and 30 runs for each of 2 through 6 failure cases. The analysis was repeated for NEA theater.

The expected CV is obtained by multiplying the average constellation value for each constellation size by the probability of the constellation being that size.

$$\text{E [Constellation Value (CV)]} = \sum_{i=0}^{24} [\text{CV}_i \times \text{P}(x = i)]$$

where x is the number of SVs. Only the cases of $i = 0, \ldots, 6$ failures were used, with a maximum possible sum of 0.992 (due to not sampling the lower tail combinations of seven or more SV failures). The expected CVs are 0.985 and 0.980 for the SWA and NEA theaters, respectively. Based on these results, there is no need to continue to treat the theaters separately in the combat outcome model.[3]

The computation of the expected constellation value for a given constellation size completes the GPS system portion of the model as depicted in Figure 6.

3.2 Tactical Air Combat Simulation Model (TACSIM) Development

The remainder of the GPS combat contribution model simulates an air-to-ground campaign, represented by the GPS combat contribution influence diagram in Figure 8. The interdependencies of the nodes represent the complex effects of improved navigation with GPS.

Using the influence diagram constructed from the GPS value tree, a deterministic simulation spreadsheet model was developed to simulate the effect of GPS navigation in air-to-ground combat. The simulation was run for two cases: GPS used for navigation, weapons guidance, and delivery; and a campaign conducted without the aid of GPS.

The model simulates a wing of 72 similar aircraft, each capable of two sorties per day and carrying two weapons per sortie. The target set is unlimited. The

[3]Sensitivity analysis, described in Section 4.3, verified only minor sensitivity of combat outcome to small changes in CV. Thus, the delta between theater E[CV]'s was within our range of indifference.

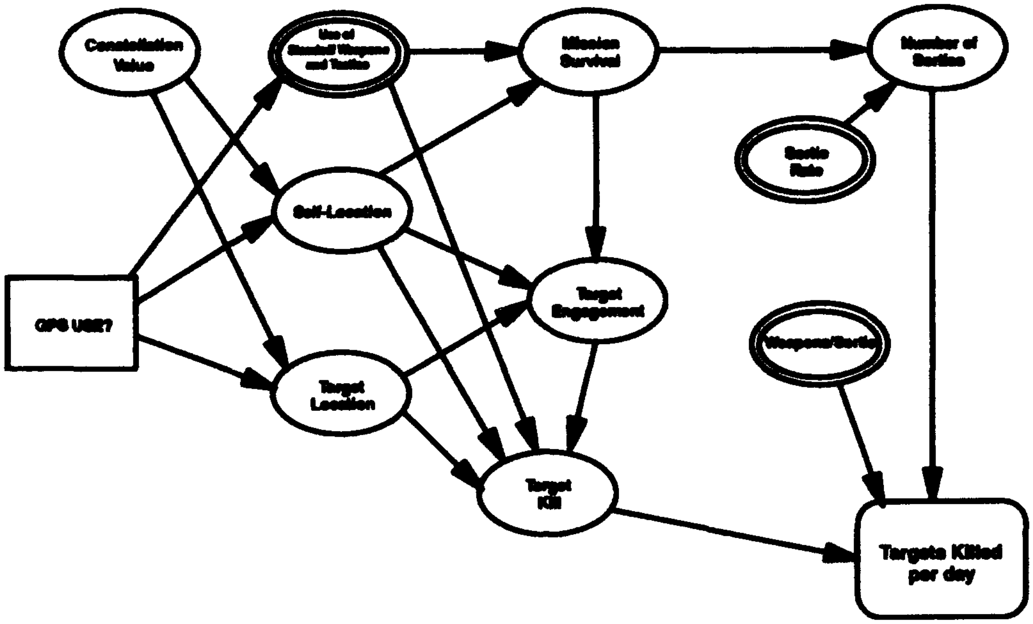

Figure 8. GPS TACSIM Influence Diagram

simulation runs for 30 campaign days and statistics are collected on the total number of targets killed, mean number of targets killed per day, and the cumulative attrition of aircraft. The probabilities for node outcomes and their underlying assumptions are discussed in the following sections.

3.2.1 Decision to Use GPS. The decision node is defined as the choice to use GPS for navigation and weapons guidance. If GPS is chosen, all 72 aircraft are assumed capable of GPS navigation and precision-guided munitions (PGM) delivery.

3.2.2 Self Location Accuracy. This node reflects the increased accuracy of navigation with GPS receivers and is a function of both the decision to use GPS and the constellation value. The outcomes of this event are defined as three accuracy classes: 'High' self location accuracy with a circular error probable (CEP) of less than 100 meters, 'Medium' accuracy with CEPs ranging from 100 to 1000 meters,

Table 8. Self Location Accuracy Distributions

Self Location Accuracy	Low CEP > 1000m	Medium 100m $\leq$ CEP $\leq$ 1000m	High CEP < 100m
GPS	$0.2 \times (1 - 0.98 \times \mathrm{CV})$	$0.8 \times (1 - 0.98 \times \mathrm{CV})$	$0.98 \times \mathrm{CV}$
No GPS	0.15	0.80	0.05

and 'Low' accuracy with CEPs greater than 1000 meters, as shown in Table 8. The probability of the sortie's self-determined location having a CEP less than 100 meters from true location was subjectively assessed as $0.98 \times \mathrm{CV}$ for a best-case GPS navigation system versus 0.05 for an INS-only system. The high probability of a military P-code GPS receiver self-locating to within 100 meters of true location is based upon the GPS available position accuracy of 8 meters CEP; the probability is reduced slightly to allow for equipment malfunction. For the no-GPS case, the lower probability of high accuracy self location reflects the fact that INS drifts at the rate of the square of time of flight (9); even the ring-laser gyroscopes in the F-15E Strike Eagle have a drift rate of tens of feet per hour and certainly benefit from GPS position updates throughout the mission and immediately prior to target engagement (21).

3.2.3 Target Location Accuracy. Target location accuracy is the node that represents target accuracy CEP as provided to the aircrew or the weapon itself. The very high dependence of target engagement and kill on accurate target location data, especially for PGM and the Joint Direct Attack Munition (JDAM-1) (9, 5), requires these bounds to be tighter than those for self location. The target CEP probabilities are again subjectively assessed for the GPS and no-GPS cases, and listed in Table 9. Because of the magnitude of errors induced by remote sensors and the lower target coordinate CEPs required, the GPS target location probabilities are lower than for GPS self location.

Table 9. Target Location Accuracy Distributions

Target Location Accuracy	Low CEP > 100m	Medium $10\text{m} \leq \text{CEP} \leq 100\text{m}$	High CEP < 10m
GPS	$0.5 \times (1 - 0.70{\times}\text{CV})$	$0.5 \times (1 - 0.70{\times}\text{CV})$	$0.70{\times}\text{CV}$
No GPS	0.15	0.80	0.05

3.2.4 Use of Standoff Weapons and Tactics. The definition of a standoff sortie is one that engages a target from a distance using PGM or JDAM-type weapons. Sorties that do not use standoff weapons and tactics are assumed to deliver conventional iron bombs.

The proportion of sorties using standoff weapons and tactics is a deterministic event node, dependent upon weapons availability, the decision to use GPS, and the constellation value available in-theater. When GPS is used, the proportion of total sorties using standoff weapons and tactics is assumed at 0.25. If JDAM-1 and more GPS-equipped platforms and weapons become available, the fraction of PGM tonnage and sorties could increase significantly above 0.25. When GPS use is not selected, the proportion drops to 0.10, which is consistent with data published following Desert Storm: the PGM fraction of total Desert Storm bomb tonnage dropped by the US Air Force was about 0.11 (7:28).

3.2.5 Mission Survival. The probability of aircraft mission survival is a function of the enemy threat, whether the sortie is employing standoff or conventional weapons, and the accuracy of the self location data. Survivability is frequently expressed in terms of attrition rates, which shrank from 0.08 in World War II to about 0.01 prior to Desert Storm (3:119,332). Pre-war estimates of Gulf War attrition ranged from 0.005 to 0.02, but the unusual circumstances of the conflict resulted in a loss rate of only 0.00047 (7:34). Because they were the most recent statis-

tics available, these figures were used in the assessment of mission survival for this simulation.

The probability assessments are listed in Table 10. The P(survival) for the non-standoff case with high self location accuracy is equal to the Desert Storm rate of 0.9995; for medium accuracy it is assessed at 0.995, the most optimistic estimate prior to Desert Storm. For low self location accuracy and non-standoff weapons, the P(survival) is the lowest at 0.991, which is approximately the figure offered by Ball (3:332) before PGM weapons saw wartime use. For sorties employing standoff weapons, the probabilities are all slightly higher than for the non-standoff case.

Table 10. Assessments for Probability of Mission Survival

	Self Location Accuracy		
	Low	Medium	High
Non-Standoff	0.991	0.995	0.9995
Standoff	0.993	0.997	0.9997

3.2.6 Engagement. The probability of target engagement is the likelihood of the weapon delivery platform actually engaging a target. It is a direct function of the platform's self location accuracy and the accuracy of target coordinates, given the survival of the platform. This probability is higher when high accuracy navigation and weapons guidance systems (such as GPS) can ensure all-weather delivery and standoff capability. Current precision-guided weapons are limited not only in their ability to engage optically-obscured targets, but also by the performance and reliability of the target designation or recognition system (seeker, laser, etc.). The notional assessments for the P(engagement) in Table 11 are intended to reflect the difficulty in engaging targets as position accuracies are degraded.

3.2.7 Target Kill. The next node represents the probability that given target engagement, a specific weapon type, and a set of target and self location

Table 11. Assessments for Probability of Engagement

		Self Location Accuracy		
		Low	Medium	High
Target Location Accuracy	Low	0.40	0.40	0.60
	Medium	0.40	0.60	0.60
	High	0.60	0.60	0.95

accuracies, the weapon will hit its target. For this analysis, all targets are assumed equal in enemy air-defense protection, hardness, and target value. Additionally, a target hit is assumed to represent a target kill. The P(kill) values were assumed to range between 0.05 for the most inaccurate self location and target accuracy outcome combinations, and 0.95 for the most precise combination (Table 12). The P(kill) values for other outcome combinations are arbitrary assessments of the ability of a delivery technique under certain location accuracies to place a weapon on target.

Table 12. Assessments for Probability of Kill

Conventional Weapons Delivery				
		Self Location Accuracy		
		Low	Medium	High
Target Location Accuracy	Low	0.05	0.10	0.20
	Medium	0.15	0.30	0.50
	High	0.60	0.70	0.80

Standoff Weapons Delivery				
		Self Location Accuracy		
		Low	Medium	High
Target Location Accuracy	Low	0.05	0.25	0.45
	Medium	0.60	0.60	0.70
	High	0.80	0.85	0.95

3.2.8 Sortie Rate. The deterministic sortie rate selected for this simulation is two sorties per day per available aircraft. Information from Desert Storm suggests that the rate could be as high as five or six per day for the two scenarios involved in this analysis (7).

3.2.9 Number of Sorties. The number of sorties flown during a 30-day campaign is limited by the number of aircraft surviving each day and the sortie rate constraint. For each campaign day, the aircraft attempt to fly two sorties each, but some are lost , attrition.

3.2.10 Number of Weapons per Sortie. The number of weapons carried per sortie is held at two; the use of larger quantities will have a multiplicative effect on the number of targets killed per sortie.

3.2.11 Targets Killed per Day. The selected measure of combat outcome was the number of targets killed per day. This quantity is the product of the number of aircraft available per day, the number of sorties flown per day (2), the number of weapons per aircraft (2), and the probability of kill for any single weapon.

3.3 Summary

The modeling of the GPS constellation is achieved through the use of IRIS simulation data for constellation size forecasting, and the results used to calculate PDOP and an expected value for the constellation value. Constellation value is used to modify distributions of self location and target location accuracies for a GPS scenario, which, in turn, determine probabilities of mission survival, target engagement, and target kill. These variables derive a probability of kill for any weapon used in the campaign.

The TACSIM model was developed in a Microsoft *Excel* workbook as a series of cross-linked spreadsheets. The flow of model data and parameters is automatic,

with the most significant variables entered into their own dedicated spreadsheet; i.e., the IRIS forecast results are printed to a data file which is loaded into its own *Excel* spreadsheet, sorted, and analysed. The resultant probability distribution is then transferred to a constellation value spreadsheet, which computes an expected constellation value using the IRIS distribution and the associated constellation values obtained from previous PDOP calculations. This cross-linking of data eases scenario and model analysis.

IV. Analysis of Results

The GPS TACSIM model used the baseline values developed in Chapter III to obtain baseline results for air-to-ground campaigns conducted with and without GPS. These results were validated and a deterministic sensitivity analysis was performed to determine the most significant variables. A stochastic simulation was then conducted to observe variance. The relationships between variables were then analyzed to improve the understanding of GPS' contribution to campaign results.

4.1 Initial TACSIM Results

The TACSIM model results for the baseline case are plotted in Figure 9. The number of targets killed in a 30-day campaign with GPS used for navigation and weapons guidance was 5167, which is 3.65 times the 1415 targets killed without the use of GPS. The analysis of these results is discussed in succeeding sections.

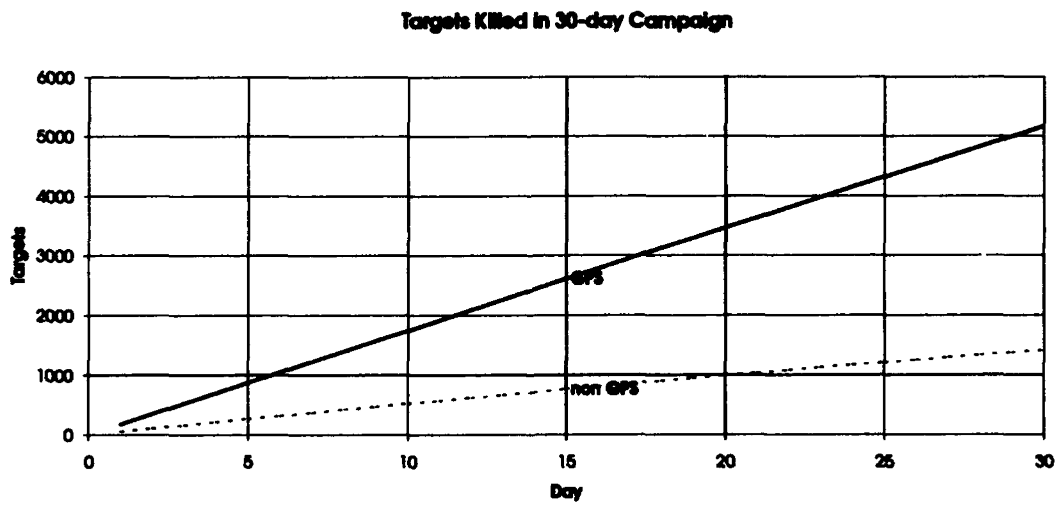

Figure 9. Baseline Results for GPS TACSIM Model

4.2 Model Verification and Validation

The GPS TACSIM model was verified by constructing a probability tree accounting for all possible combinations of TACSIM event outcomes. The probability tree results (included in Appendix B) matched those obtained from the model, verifying the accuracy of the model's algorithms. The probabilities were analysed for the GPS and no-GPS scenarios to validate the model's behavior (20:104).

4.2.1 GPS Results. In a perfect case with probabilities of survival, engagement, and kill all equal to 1.0, each of 72 aircraft, flying two sorties per day and carrying two weapons per sortie, could destroy 288 targets per day. Accordingly, the absolute best possible result from a 30-day campaign would be 8640 targets destroyed. Any performance below this level can be attributed to less than perfect probabilities of survival, engagement, and kill. Using the values from the probability tree, the difference in the GPS versus no-GPS campaign outcomes was investigated. The contributions of these parameters are shown in Figure 10.

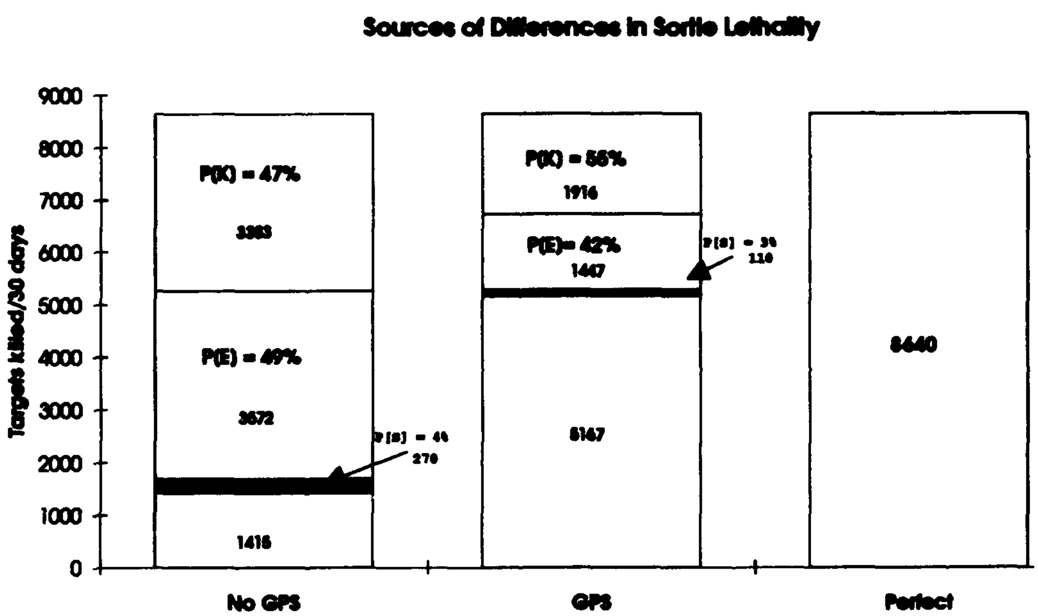

Figure 10. Identification of Limiting Variables for TACSIM Results

For the GPS case, the most significant degradation is due to P(kill), accounting for 55% of the total difference in targets killed. This relationship is not surprising, since only 0.25 of the GPS sorties use the more effective standoff weapons. The results could be improved by using a higher proportion of standoff weapons, and by increasing the probability of high-accuracy self location and target location outcomes.

The P(engagement) variable, accounting for 42% of the degradation, is the second largest limiting variable in the GPS campaign. As a direct function of the accuracy of self and target location data, P(engagement) suffers from inaccurate navigation information and poor targeting data.

P(survival) contributes only 3% to the overall results because of the very low attrition levels assigned to the campaigns.

4.2.2 No-GPS Results. Again referring to Figure 10, the no-GPS campaign results are most significantly reduced due to the somewhat balanced effects of P(engagement) (contributing 49%) and P(kill) (contributing 47%). With notional P(engagement) assessments averaging 0.60 due to predominantly 'medium' navigation accuracies, the number of sorties releasing bombs over their assigned target is constrained. When the sorties do engage their targets, the imperfect P(kill) due to a lower proportion of standoff sorties (0.10) and less accurate self and target location data account for a significant degradation. The variable contributing the least to the no-GPS results is P(survival), which is always at least 0.991 and accounts for only 4% of the difference.

A second comparison of the GPS and no-GPS results is made in Figure 11. In this figure, the difference between the no-GPS and GPS results is again distributed among the effects of P(survival), P(engagement), and P(kill). In this comparison, P(engagement) at 57% is the most significant contributor to the increase in targets killed for the GPS case.

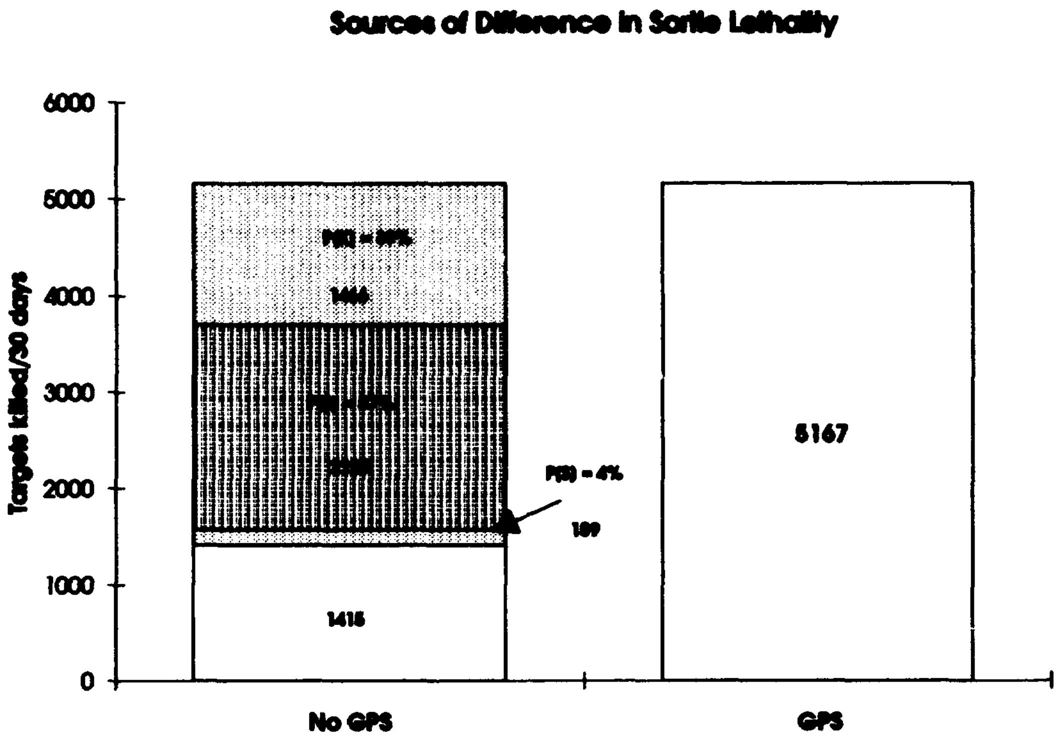

Figure 11. Comparison of GPS and No-GPS TACSIM Results

The next most significant driver is the increase in P(kill) obtained with GPS navigation and weapons. Part of the 39% increase is due to the 0.15 increase in the proportion of standoff weapons used in the GPS campaign over the no-GPS, but the remainder is attributable to the increased iron bombing accuracy obtained with GPS. Bombing tests at Yuma Proving Grounds have shown that when aircraft use GPS for self location and/or target coordinate updates, delivery CEPs are improved by approximately 50% (11:147).

The least significant contributor was a slightly higher rate of attrition for the no-GPS case, accounting for only 3% of the difference.

4.3 Sensitivity Analysis

The next step in analyzing the TACSIM model was the deterministic sensitivity analysis of the independent variables. Each variable was shifted from the base value

to an upper and lower bound and the results compared to determine which variables might require more detailed study. The lower and upper limits were approximated at the 0.05 and 0.95 cumulative probability levels of the estimated range of values for each variable (6).

As shown in Figure 12, TACSIM is most sensitive to the sortie rate per day and number of weapons carried per sortie; the attrition rate is a function of the sortie rate and the number of targets killed is a multiple of the number of the weapons. These variables merely scale the overall TACSIM results.

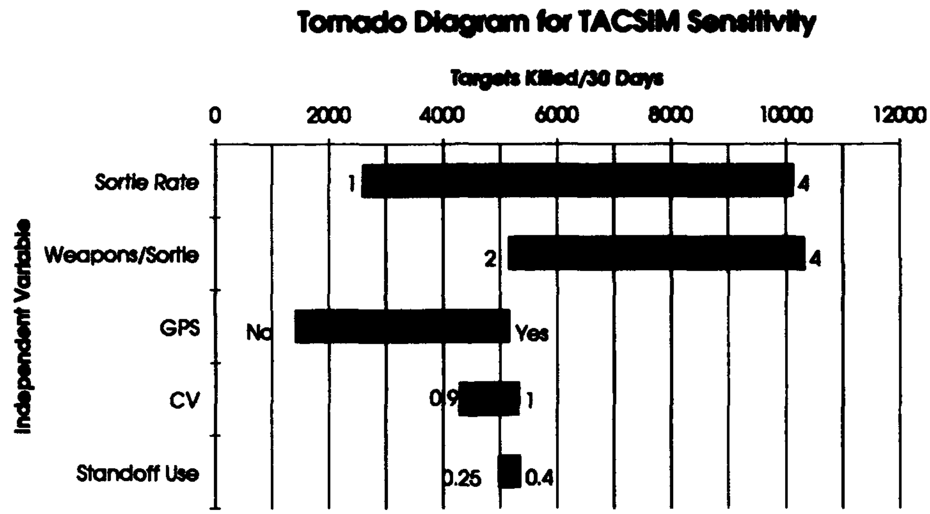

Figure 12. TACSIM Sensitivity Results

The next most significant variable is the decision to use GPS. When GPS is not used for navigation and weapons guidance, the sortie lethality is reduced as discussed in the previous section.

Variations in constellation value influence the results to a lesser extent. As shown in Figure 13, TACSIM results are very sensitive to CV. However, for most decisions that AFSAA is expected to face, it is anticipated that none will involve significant reductions in the baseline GPS constellation size; the decisions will likely involve whether to delay the replacement of a single, or at most three, SV failures.

And as shown in Table 7, the mean constellation value for 3 SV failures is about 0.98. Thus, the constellation-induced risk to campaign success and duration appears minimal for small reductions in constellation size.

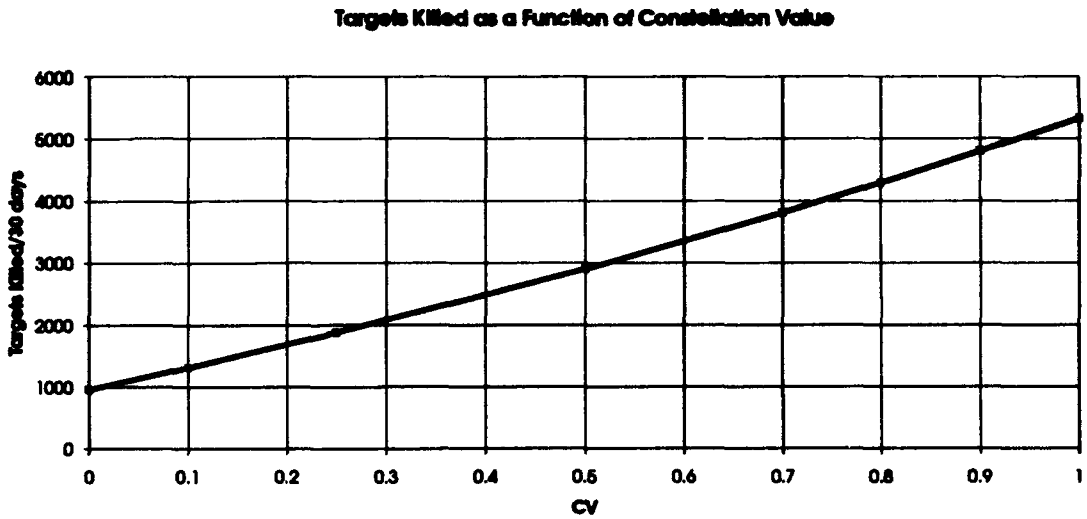

Figure 13. Sensitivity of TACSIM Results to Constellation Value

The least significant variation in campaign outcome is due to the proportion of standoff sorties flown. The base case proportion was assessed at 0.25, and could feasibly vary between 0.10 and 0.40. Because these tactics have a higher survival rate and the weapons a higher P(kill) given favorable target location data, they have a higher probability of success. Thus, if the standoff weapons are available in affordable quantities, the campaign can realize significant gains by using a higher proportion of standoff weapons, as seen in Figure 14.

Although TACSIM is not sensitive to all of the independent variables, they were retained in the model as a tool for subsequent analysis of the dependent variables.

4.4 *Monte Carlo Simulation*

To better characterize the TACSIM model behavior, a Monte Carlo simulation was conducted (6:313). The constellation value, proportion of standoff sorties, and

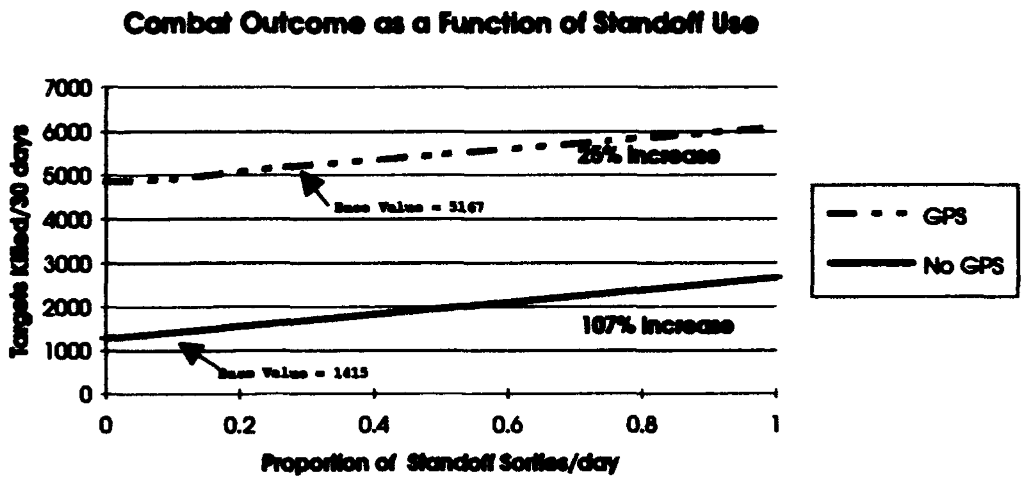

Figure 14. Effect of Standoff Use on Campaign Outcome

probabilities of engagement and kill were all converted to random variables. The Beta distribution was chosen for all variables because of its ability to model any parameter with values between 0 to 1. The probability of survival was not varied due to the relative certainty of the base values.

The TACSIM 30-day campaign was simulated 30 times for both the GPS and the no-GPS scenarios. The sample size of 30 independent runs can be shown to adequately estimate the true mean of the stochastic model to within 2σ, if the 2σ accuracy is defined as 50 targets:

$$\text{Minimum Sample Size} = [2 \times \frac{std\ dev}{Accuracy}]^2 \qquad (17:368)$$

where the standard deviation from the Monte Carlo runs is used as an estimate of the true standard deviation. This level of fidelity is appropriate for the purpose of this research.

The simulation results are listed in Table 13. In the GPS case, the mean number of targets killed over 30 days (5071) differed from the deterministic result of 5167 by only 2%; the standard deviation was only 91 targets. This effect was also

Table 13. Monte Carlo Simulation Results

Campaign	Mean Targets Killed	Standard Deviation	Deterministic Result
GPS	5071	91	5167
No-GPS	1491	111	1415

observed in the no-GPS campaign, where the mean number of targets killed (1491) was only 5% above the deterministic value of 1415, and the standard deviation was 111.

The cumulative distribution functions for both scenarios are also shown in Figures 15 and 16, revealing the narrow distribution of the simulation outcomes and confirming the stochastic dominance of the GPS over the no-GPS campaign results (6:90).

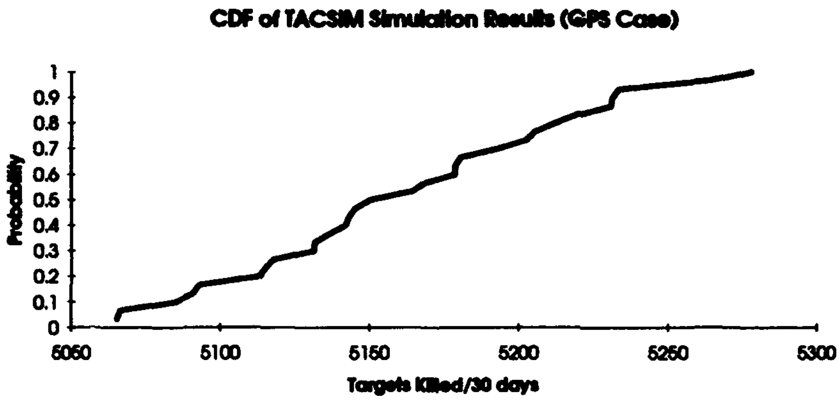

Figure 15. Cumulative Distribution Function (GPS Case)

4.5 *Navigation Sensitivity Analysis*

The behavior of the model was next investigated through a detailed analysis of sensitivity to the navigation variables.

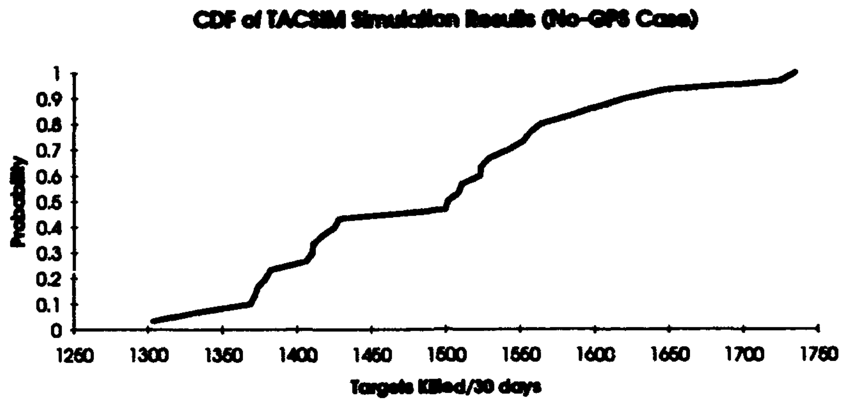

Figure 16. Cumulative Distribution Function (No-GPS Case)

Recall that the only difference between the GPS and no-GPS campaigns is the distribution of self and target location accuracies and the proportion of standoff sorties flown. The effect of improved navigation is very clearly seen in Figure 17, where the range of high self and target location accuracy probabilities can be seen to account for the entire range of the no-GPS and GPS campaign results. This relationship demonstrates the magnitude of the contribution of GPS navigation and its potential to improve sortie lethality.

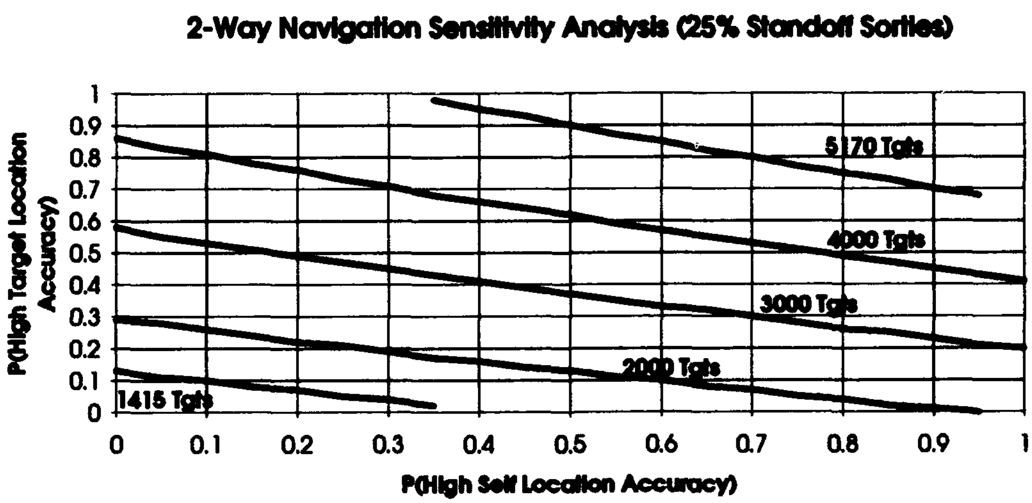

Figure 17. Sensitivity to Navigation Accuracy

The difference in results between two isocount lines can be translated into the time required to kill a fixed number of targets. For example, consider the degradation in campaign outcome for the 4000 isocount line ([5167 − 4000] = 1167 targets per 30 days). By computing a mean number of targets killed per day (133.3), there is a potential delta of almost nine days required to accomplish the base case result of 5167 targets. In campaign terms, this may be interpreted as an additional nine days to achieve a campaign objective of 5167 targets. The implications of such a delay in a modern, short-duration campaign could be severe.

In order to further isolate the effect of improved self and target location accuracy, the standoff proportion was set to zero. The subsequent outcome of 4861 targets killed/30 days identifies the surprising fact that, given the baseline parameter assessments, only about 6% of the base case results were due exclusively to the use of PGM and JDAM weapons and their higher P(kill). The lethality of conventional, unaided weapons is enhanced simply by the higher accuracy of self location and target location data and the resulting higher survivability, engagement, and kill probabilities.

4.6 Weapons Effectiveness Analysis

To investigate the effect of weapons effectiveness on TACSIM behavior, the variables of P(engage | high self location and target location accuracy) and P(kill | non-standoff, high self location and target location accuracy) were varied simultaneously. The TACSIM model exhibits a considerable sensitivity to these assessments, as evidenced in Figure 18. As these parameters are assessed at values lower than the original parameters in Chapter III, the outcome of the GPS campaign can approach the lower, no-GPS campaign result. Because of this sensitivity, the actual variables used in the application of TACSIM should be provided by credible sources such as the Joint Munitions Effectiveness Manual (JMEM).

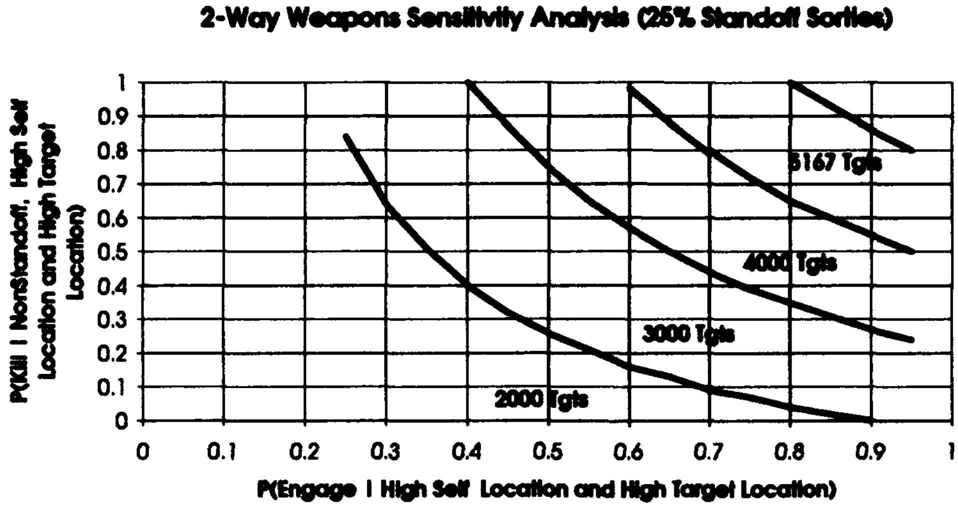

Figure 18. Sensitivity to P(Engagement) and P(Kill)

4.7 *Enemy Exploitation of GPS*

One objective of this research was to assess the impact of enemy exploitation of the GPS system. Although this problem was not modeled explicitly by TACSIM, it can be derived by analyzing the effects of GPS navigation accuracy on the parameters affecting sortie lethality.

As discussed in Chapter II, the GPS signal is broadcast in two code formats. Only the low-precision C/A code is available to unauthorized users; thus, the accuracy available to an opponent is limited to 40 meters CEP (assuming he does not use the Russians' similar GLONASS system, which does not deny access to the high-accuracy codes). Recalling the bounds for high self and target location accuracies, it is apparent that even though the enemy is only using the SPS, his self location accuracy is less than 100m CEP and assessed as 'high.' A similar comparison with target location accuracy reveals that he will only experience 'medium' target location accuracy. Both the self and target location accuracies are functions of the GPS CV. Based on these definitions, the enemy's expected navigation accuracies are shown in

Table 14. Enemy Navigation Accuracy with GPS SPS Use

Self Location Accuracy		
Low CEP > 1000m	Medium 100m $\leq$ CEP $\leq$ 1000m	High CEP < 100m
$0.2 \times (1 - 0.98 \times \text{CV})$	$0.8 \times (1 - 0.98 \times \text{CV})$	$0.98 \times \text{CV}$

Target Location Accuracy		
Low CEP > 100m	Medium 10m $\leq$ CEP $\leq$ 100m	High CEP < 10m
$0.8 \times (1 - 0.70 \times \text{CV})$	$0.70 \times \text{CV}$	$0.2 \times (1 - 0.70 \times \text{CV})$

Table 14. The TACSIM model can then be used to determine the expected impact to the enemy's campaign results. Assuming the enemy is not using standoff weapons and that he enjoys similar probabilities of survival, engagement, and kill as our own forces, the TACSIM model computed 2452 targets killed over 30 days (almost a 75% increase from the no-GPS case).

This model of sortie effectiveness can be used to estimate the effect of an enemy's use of GPS for his own navigation purposes, even when he only accesses the civilian SPS signal. The potential for increased enemy lethality places even more pressure on our air forces to achieve campaign objectives quickly.

4.8 Summary of TACSIM Results

Through the TACSIM deterministic model simulation, Monte Carlo simulation, and deterministic sensitivity analysis the reasons for the increase in GPS campaign results were identified and explained. It is apparent that, for the assumptions we made for this analysis, GPS navigation has a measurable impact on sortie lethality, attributable to three primary factors:

- GPS navigation enhances lethality through higher probability of self location accuracy within a 100 meter CEP. This enhancement alone impacts sortie survivability, probability of engagement, and probability of kill. But the synergistic effect of accurate target and self location information can increase these parameters to very high levels of effectiveness.
- GPS navigation increases lethality through increased target location accuracy; the higher probability of locating a target to a CEP of less than 10 meters has a dramatic influence on probability of engagement and target kill, whether PGM or unaided weapons are used.
- GPS navigation provides an inexpensive means of aiding conventional iron weapons (JDAM-1) (5), affording a potentially higher fraction of standoff sorties and a resultant higher probability of kill.

These influences are shown to be somewhat insensitive to random fluctuations in the GPS constellation size. Only in the unlikely event of 5 or more simultaneous SV failures does the GPS accuracy degrade significantly and begin to approach the no-GPS levels.

The analysis has also shown the dependence of the campaign outcome on the choice of parameters for P(survive), P(engage), and P(kill). The values used in the TACSIM base case are notional, and require modification by the user to more accurately represent the campaign outcomes both with and without GPS.

V. Conclusions and Recommendations

This final chapter discusses conclusions based on the results of analysis of the GPS and no-GPS campaigns, and proposes issues for further research.

5.1 Conclusions

The primary objective of this research was to develop a method to measure the effects of varying constellation size on the contribution of the GPS system to combat outcome. The study concludes that for the current 24 SV constellation baseline, there is a minimal chance of experiencing six or more simultaneous SV failures. And for most combinations of six failures, the resulting GPS accuracy degradation does not appear to significantly degrade air-to-ground combat outcome in either the SWA or NEA theaters, for the notional weapon system effectiveness parameters used in this analysis. Given actual parameters, the TACSIM model provides a means to more accurately assess the impact of constellation size decisions.

Additionally, the research identifies the effect of improved navigation accuracy on air-to-ground combat outcome. An increase in targets killed over time is attributable to the synergistic effects of high accuracy navigation and target data on probabilities of sortie survival, engagement, and kill. The study identifies the GPS-related enhancement of these MOEs, which can be used in larger air campaign models to more accurately quantify the effects of GPS navigation on air-to-ground sortie lethality.

A secondary objective of the research was the development of a space system contribution assessment method that could be adapted to other military space systems. The use of the decision analysis techniques of influence diagrams and value trees facilitated the measurement of the campaign contribution of the GPS space system, and they are directly applicable to other space systems. Influence diagrams can be used to identify the major factors affecting constellation size, and ultimately,

system availability and accuracy. The value tree is used to develop operational attributes of air-to-ground campaigns that would capture the influence of the space system on the campaign scenario. The two tools are combined to develop either a unique theater air combat simulation, or to identify the campaign parameters or 'hooks' to be modified and observed in an existing campaign model.

Finally, the research was intended to assess the impact of enemy use of GPS against our own forces. Analysis of this exploitation reveals that even with access to only the SPS signals, an adversary can realize a significant increase in the number of targets killed over time.

5.2 Recommendations

This research identifies a means to assess the contribution of the GPS space system to the air-to-ground warfighter. However, in order to more clearly understand the contribution of GPS to any campaign, more study is needed in several critical areas:

- The definition of Constellation Value included a threshold of PDOP$\leq$6.0. The threshold could possibly be redefined to consider PDOP$\leq$2.5, more closely approximating the actual GPS PPS accuracy specification and demonstrating more variation and sensitivity to SV failures.
- Due to the model's sensitivity to the assessment of self location and target location accuracy probabilities, these parameters should be studied to ensure they reflect current navigation and targeting accuracies.
- The effort required to formulate the GPS contribution methodology coupled with the data classification precluded a more accurate assessment of the critical probabilities for sortie survival, engagement, and kill. These parameters should be investigated and more closely related to self location accuracy, target location accuracy, and weapon CEPs.

- The MOEs identified in the research are common to large-scale air campaign models. Future research could adapt the GPS constellation model and related location accuracies to an air campaign model; the results would be of much higher fidelity and credibility.
- The threat of GPS signal jamming was assumed to be negligible for this analysis. However, the methodology provides a means to degrade or deny GPS signals through the 'signal survivability' node. Future research could characterize the jamming threat for inclusion in the model.

Appendix A. Expected Constellation Value Data

A.1 IRIS Output Data

The IRIS simulation was run as described in Chapter III. For the baseline launch schedule, the probabilities of having greater than or equal to 15 or more operational SVs on orbit were plotted as a function of time (months from September 1993). The cumulative probabilities were output as data files and loaded into an *Excel* spreadsheet. For each of the cases, the probabilities were averaged over 96 months. These mean values were used to obtain the discrete probabilities in Table 15, and used for subsequent expected constellation value computations.

Table 15. Discrete Probability of X SVs On Orbit

SVs	$P(X \geq x)$	$P(X < x)$	$P(X = x_2) = P(X < x_2) - P(X < x_1)$	$P(X \leq x)$
15	1.000	0.000	0.001	0.001
16	0.999	0.001	0.002	0.003
17	0.997	0.003	0.006	0.008
18	0.992	0.008	0.014	0.023
19	0.977	0.023	0.030	0.052
20	0.948	0.052	0.069	0.121
21	0.879	0.121	0.139	0.260
22	0.740	0.260	0.196	0.456
23	0.544	0.456	0.253	0.709
24	0.291	0.709	0.291	1.000

A.2 Constellation Availability and Constellation Value

Constellation availability was measured by PDOP, which was forecast using Lieutenant Colonel T.S. Kelso's PDOP computer program. This program is programmed in PASCAL and compiled for IBM-compatible PC use. The program reads user-specified time interval, time duration, geographic location, and geographic step size information from a data file, and references user-supplied USSPACECOM two-

line orbital element sets for the desired SV constellation. The results are output in a latitude/longitude grid format for each time increment specified in the user setup file. The PDOP results are next read into a constellation value program to calculate the percentage of time PDOP$\leq$ 6.0 for each location step. The CV data is also output in a latitude/longitude format.

Computation time on a 486-DX-33 PC was approximately one hour per 10 degree by 10 degree location grid (one-degree steps), computing PDOP at one minute intervals over a 24-hour period. Run time is significantly shorter when forecasting PDOP with less than 20 SVs.

The PDOP and CV software and the CV data listings used in this research are available upon request from AFIT/ENS, c/o Lt Col T.S. Kelso, 2950 P Street, WPAFB OH, 45433-7765.

Appendix B. Probability Tree Results

As part of the TACSIM model validation, two probability trees were constructed to obtain joint probabilities of sortie survival, engagement, and weapon kill based on the model assumptions. Included in this appendix is the tree for the GPS case only. The number of targets killed per day is the product of the joint probability of kill, the number of aircraft available, the number of sorties per day (per aircraft), and number of weapons carried per sortie.

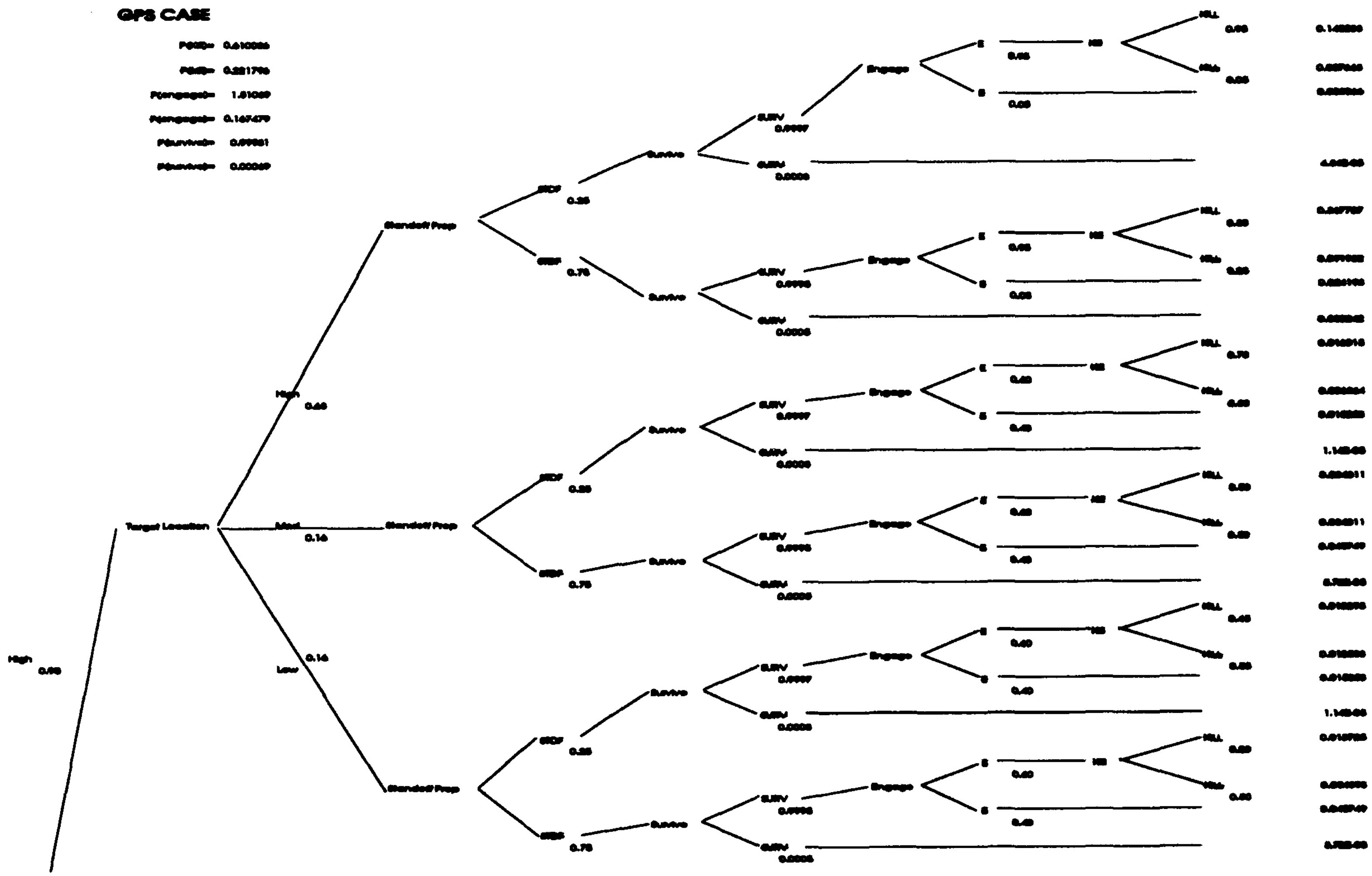

Figure 19. Probability Tree for GPS Case (High Self Location Accuracy)

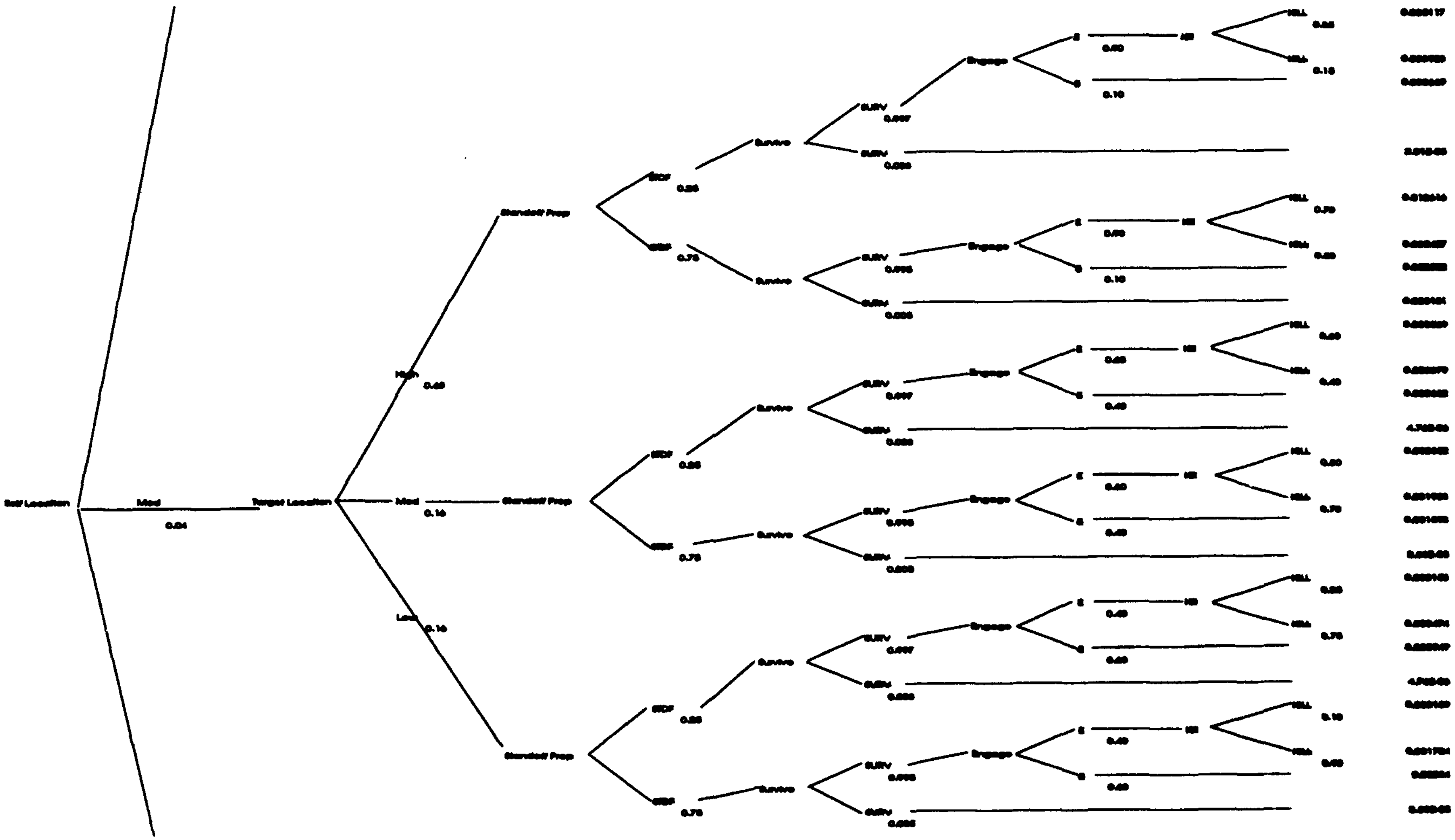

Figure 20. Probability Tree for GPS Case (Medium Self Location Accuracy)

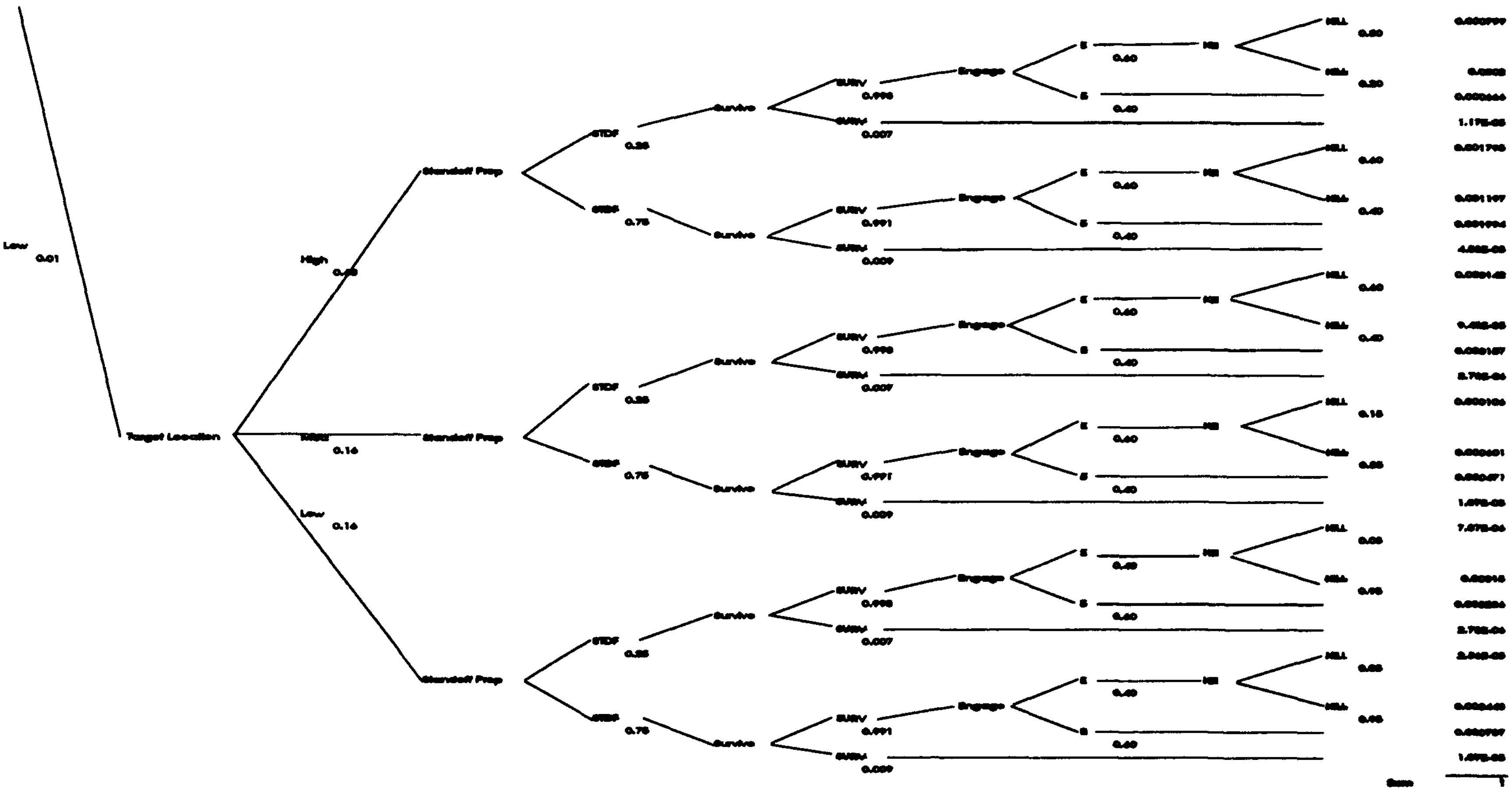

Figure 21. Probability Tree for GPS Case (Low Self Location Accuracy)

Bibliography

1. Aderhold, David J. *A Replenishment Phase Study for the NAVSTAR Global Positioning System.* MS Thesis, AFIT/GSO/ENS/84D-1. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, December 1984.
2. Allen, Patrick D. *Modeling Global Positioning Satellite Effects in the TLC/NLC Model* (Draft). RAND Corporation, DRR-260-AF/A (MR-393-AF/A), June 1993.
3. Ball, Robert E. *The Fundamentals of Aircraft Combat Survivability Analysis and Design.* AIAA Education Series, New York 1985.
4. Bird, Julie. "Space Command: New Horizons," *Air Force Times, 39*:8. May 3 1993.
5. Cerrato, Louis. *Joint Direct Attack Munition.* Unpublished briefing, ASC OL/YH-2, Eglin AFB FL, September 1993.
6. Clemen, Robert T., *Making Hard Decisions: An Introduction to Decision Analysis.* Boston: PWS-Kent Company, 1991.
7. Department of the Air Force. *Reaching Globally, Reaching Powerfully: The United States Air Force in the Gulf War, A Report.* September 1991.
8. Department of Transportation and Department of Defense. *1992 Federal Radio Navigation Plan.* January 1993.
9. Frost, Gerald P. and Bernard P. Schweitzer. "Operational Issues for GPS Aided Precision Missiles", pp. 325-337, *1993 National Technical Meeting Proceedings,* The Institute of Navigation, March 1993..
10. Giesege, Capt Bruce. Interview. National Air Intelligence Center, Wright-Patterson AFB OH, Sept 9 1993.
11. *GPS NAVSTAR User's Overview,* 5th edition, by ARINC Research Corporation for the Navstar GPS Joint Program Office, March 1991.
12. Heier, Capt Jeff. Telephone Interview. Space and Missile Center, Los Angeles AFS CA, May 20 1993.
13. Hudson, Neff. "Space Warriors Eye Final Frontier," *Air Force Times, 43*:12-13. May 31 1993.
14. HQ AFSPACECOM/DRF, "Use of OSCARS for GPS Planning and Baseline Parameters," Policy Letter, Apr 13 1993.
15. Inventory Replacement Intervals for Satellites (IRIS) User's Manual, Version 2.3, ANSER Space Technology Division for SAF/AQSL, October 1992.
16. Kent, Lt Gen Glenn A. (USAF, Retired). Telecon 4 Aug 93.

17. Mendenhall, William, Dennis Wackerly, and Richard Schaeffer. *Mathematical Statistics with Applications.* Boston: PWS-Kent Company, 1990.

18. Millburn, Lt Col Brian. Space Analyst. Telephone Interview. Air Force Studies and Analysis Agency, Washington DC, May 18 1993.

19. NAVSTAR Global Positioning System (GPS) System Operational Requirements Document (SORD), AFSPACECOM (USAF 003-78) I/II/III, Jan 22 1990.

20. Sargent, Robert G. "Validation and Verification of Simulation Models," p. 104, *Proceedings of the 1992 Winter Simulation Conference*, December 1992.

21. Sosebee, Maj Baxter. F-15E Weapons System Officer. Personal interview. Sept 27 1993.

22. Streets, Gary B. and Anita J. Adams. "Military Utility of Space Systems," AFSPACECOM/CNP, 60th Military Operations Research Society (MORS) Symposium, 23-25 July 1992.

23. The Analytical Sciences Corporation (TASC). *The TASCFORM-SPACE Methodology: A Prototype Tool for Assessing the Comparative Value of Space Systems.* TR-5771-7-1, February 28 1992.

24. Thaler, David E. *Strategies-to-Tasks: A Framework for Linking Means and Ends* (Draft). RAND Corporation, DRR-243-AF, July 1993.

25. Thomin, David W. *Global Positioning System - A Modification to the Baseline Satellite Constellation for Improved Geometric Performance.* MS Thesis, AFIT/GA/ENG/84D-4. School of Engineering, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, December 1984.

Vita

Captain Stephen F. Sovaiko was born in 1960 in Boston, Massachusetts. His family moved to the Washington D.C. area in 1962 where he spent his childhood. He was active in scouting and earned the Eagle Scout award in 1977. Following graduation from Arundel Senior High School in Gambrills, Maryland, he accepted an Air Force ROTC scholarship and entered the University of Maryland at College Park in 1978. In 1982 he graduated with a Mechanical Engineering degree, was commissioned, and entered active duty at the Air Force Weapons Laboratory at Kirtland AFB, New Mexico in 1983. While at Kirtland he conducted nuclear weapons effects tests on military aircraft and missile systems; he also met his wife Geri and they married in 1984. In 1985 he transferred to Space Command at the 7th Missile Warning Squadron, Beale AFB, California where he served as a combat crew commander and Chief of Standardization/Evaluation. Captain Sovaiko was a Distinguished Graduate from Squadron Officer School in 1987, and was assigned to Systems Command's Armament Division at Eglin AFB, Florida in 1988. While at Eglin, he served as a program manager and lead engineer for the Range Applications Joint Program Office, where he managed the development of Global Positioning System hardware for the Strategic Defense Initiative's ballistic missile interceptor. Following successful installation and test of the hardware in 1990 at Kwajalein Atoll, Marshall Islands, Captain Sovaiko managed the development of advanced surface-to-air missile threat simulators for Strategic Air Command before entering the Graduate School of Engineering, Air Force Institute of Technology in 1992. Captain Sovaiko was also awarded a Master of Science degree in Management from Troy State (Alabama) University in 1993.

Permanent address: 1742 Tarrytown Avenue
Crofton, MD 21114

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
December 1993

3. REPORT TYPE AND DATES COVERED
Master's Thesis

4. TITLE AND SUBTITLE
A Methodology to Assess the Impact of the Global Positioning System on Combat Outcome

5. FUNDING NUMBERS

6. AUTHOR(S)
Stephen F. Sovaiko, Captain, USAF

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Institute of Technology, WPAFB OH 45433-6583

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT/GSO/ENS/93D-15

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Studies and Analysis Agency, Space and C^3I Division (AFSAA/SASS), 1570 Air Force, Pentagon, Washington DC, 20330-1570

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The Air Force has a requirement to quantify the force enhancement effects of military space systems, but no methodology currently exists for the measurement of their contribution to air combat outcome. This research examines the Global Positioning System (GPS) and models its influence on air-to-ground combat. The decision analysis technique of influence diagrams is used to identify the effects of GPS launch decisions and constellation size on the navigation accuracy available to air combatants. The effect of accuracy variations on combat outcome is shown by using a value tree to identify the affected campaign Measures of Effectiveness. The study reveals that the use of GPS for navigation and weapons guidance results in a significant increase in sortie lethality that depends on the actual probabilities of survival, engagement, and kill for various weapon, platform, and target combinations. Also, the simultaneous loss of several GPS satellites is shown to have only a moderate time-averaged effect on navigation and combat outcome in the Northeast and Southwest Asia theaters. The methodology presented can be adapted to the study of other military space systems.

14. SUBJECT TERMS
Global Positioning System, Navigation Satellites, Military Satellites, Operations Research, Operational Effectiveness, Combat Effectiveness, Tactical Bombing, Decision Analysis, Space System Utility

15. NUMBER OF PAGES
69

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL